

LA-UR-21-23649

Approved for public release; distribution is unlimited.

Title: Microcalorimeters: A Bright, Bold Future

Author(s): Koehler, Katrina Elizabeth

Intended for: General purpose presentation

Issued: 2021-04-26 (rev.1)

Disclaimer:

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.



Microcalorimeters: A Bright, Bold Future

Katrina E. Koehler
(on behalf of the LANL
Low Temperature Detector team)

29 April 2021

LA-UR-21-



Managed by Triad National Security, LLC., for the U.S. Department of Energy's NNSA.

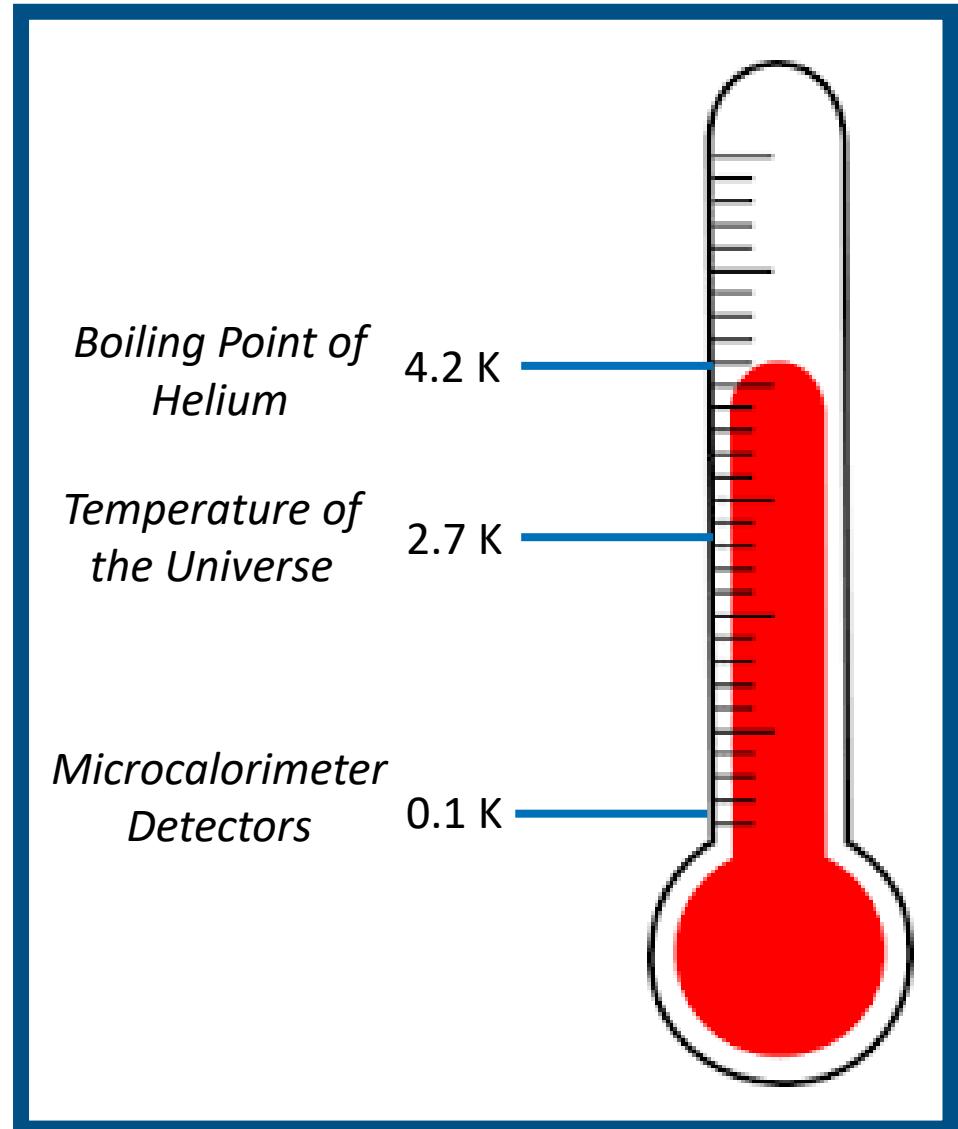
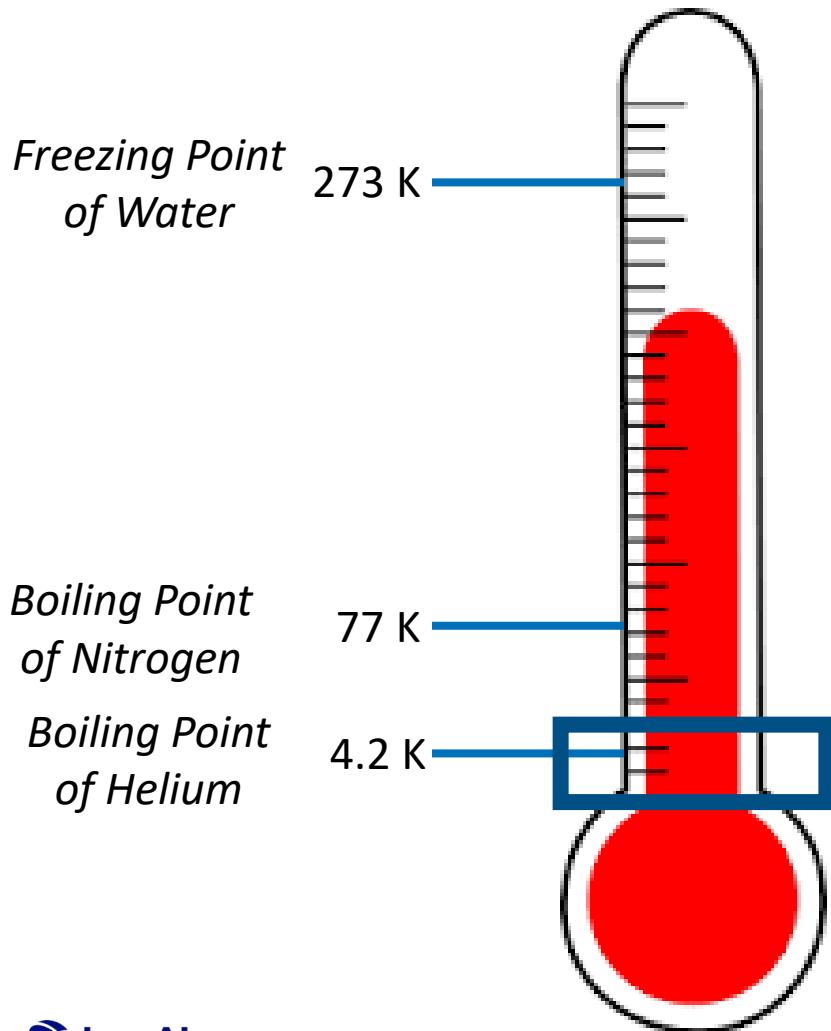
Outline

- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

Outline

- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

One of the Coldest Places in the Universe

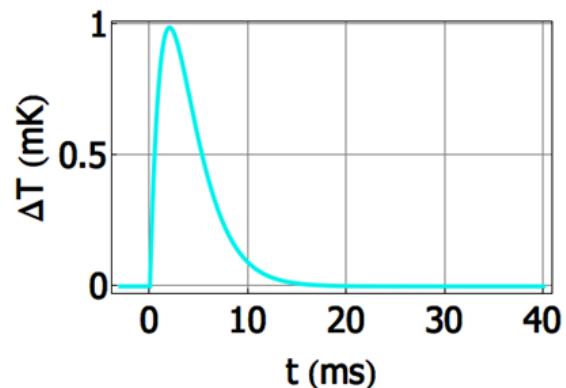
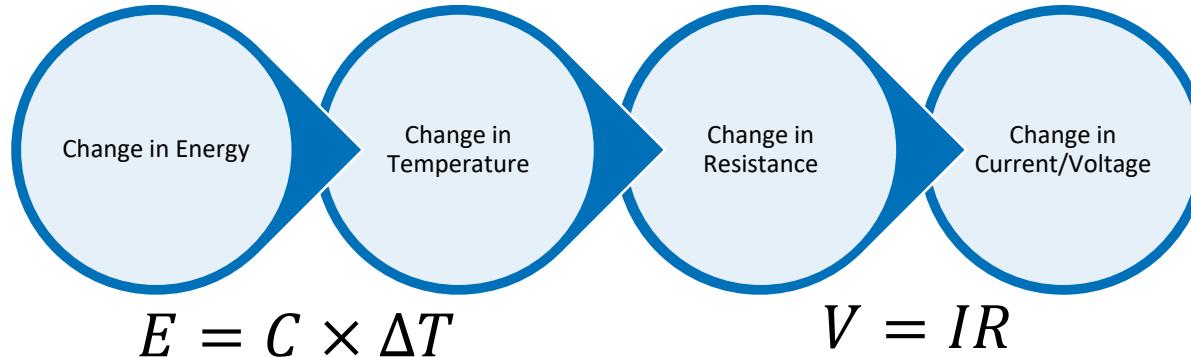
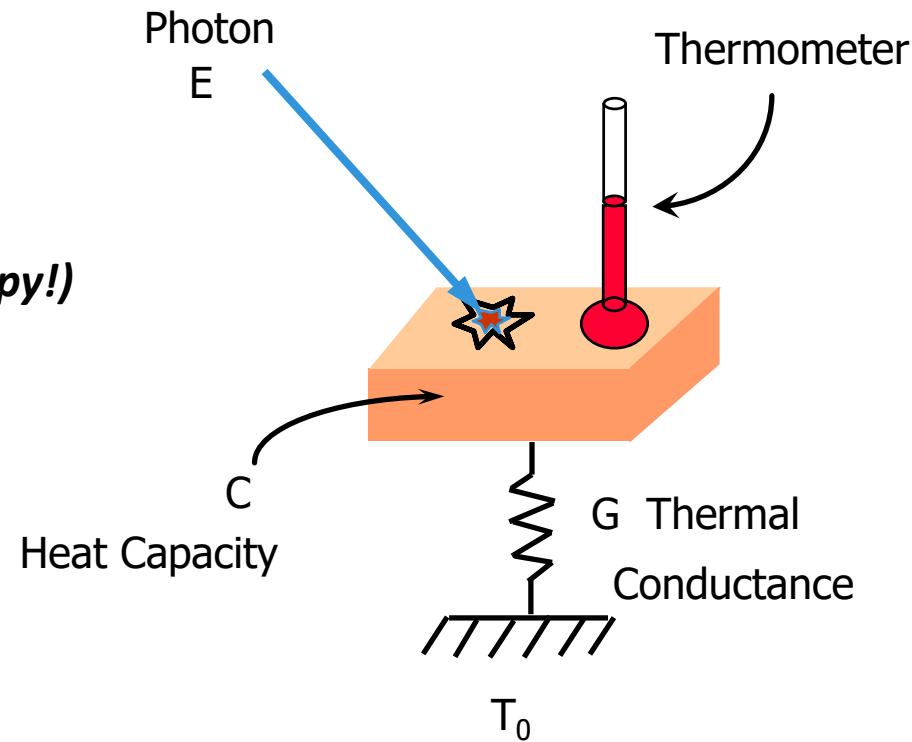
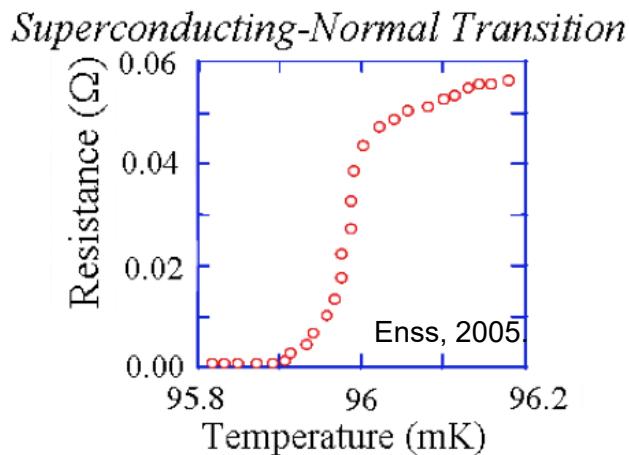


Microcalorimeter

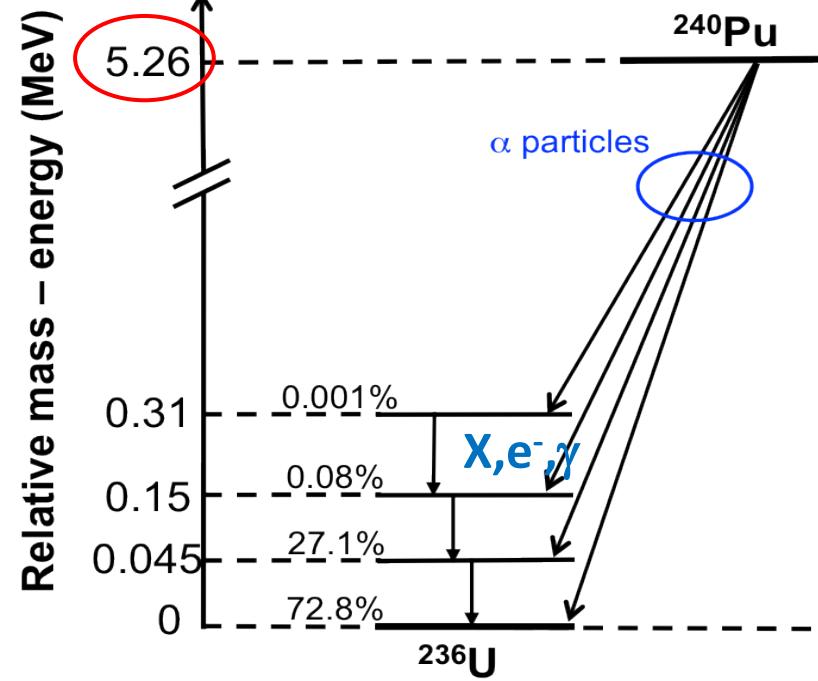
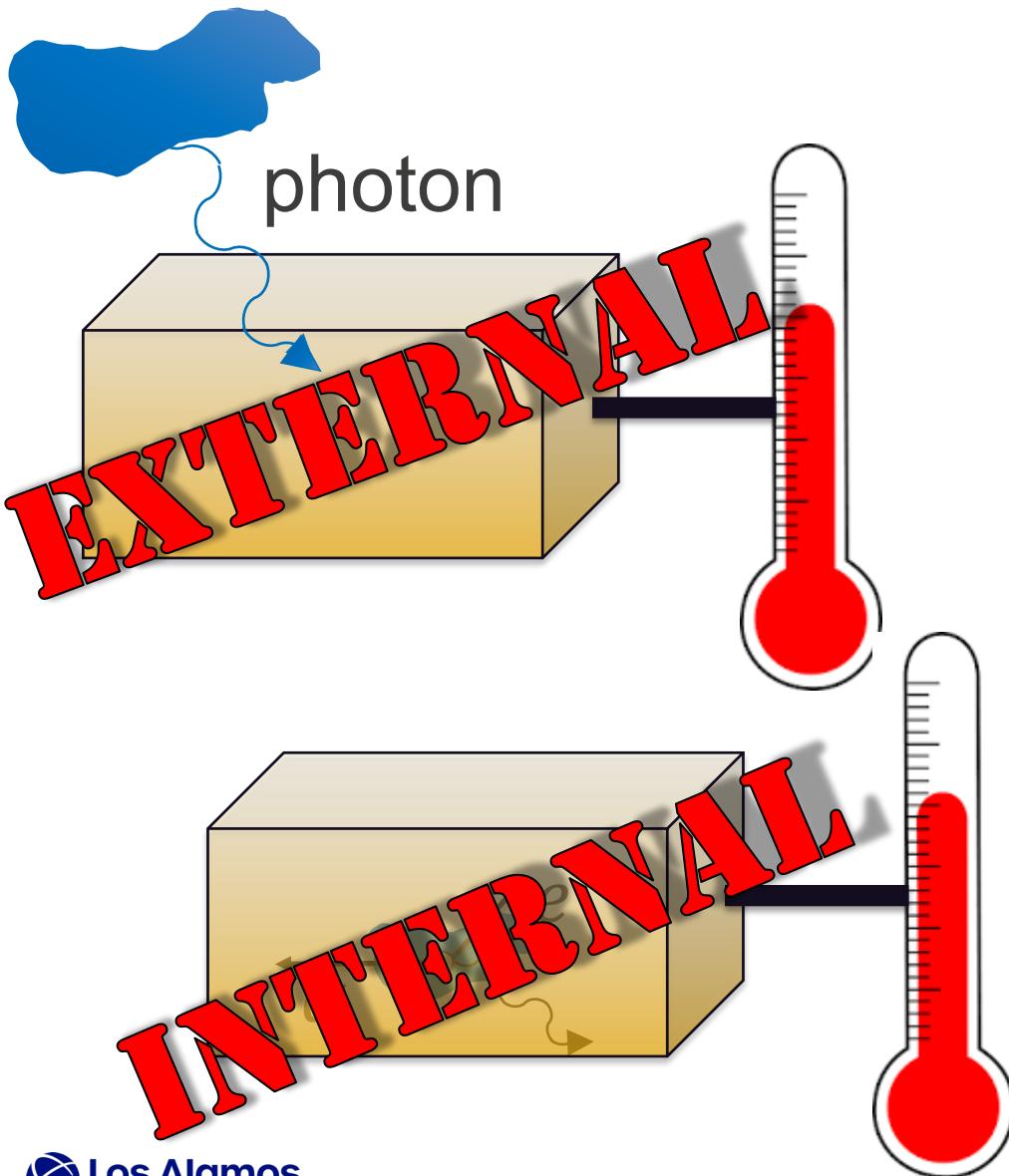
Turn kinetic energy into heat →

Measure with a sensitive thermometer →

Histogram energy from each event (Spectroscopy!)



Microcalorimeter



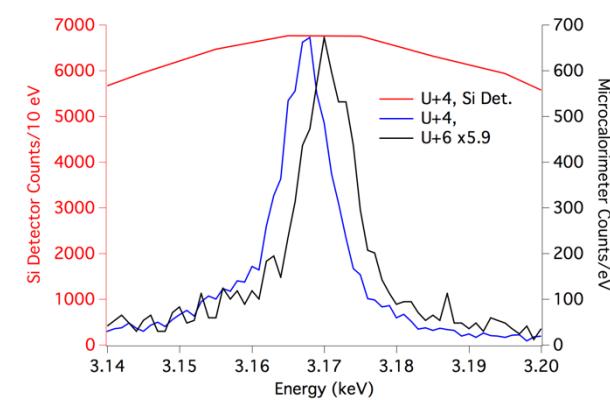
Key microcalorimeter advantage:

10x better energy resolution than semiconductor detectors

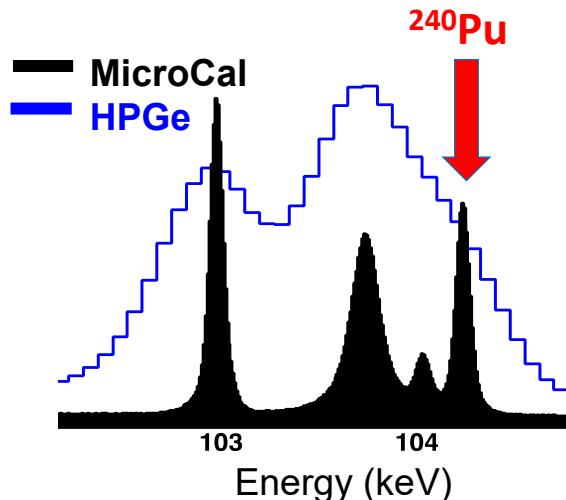
$$\Delta E \approx \sqrt{4kT^2 C}$$

100 mK

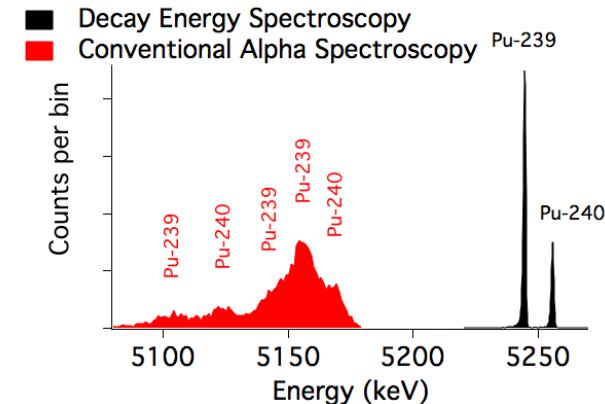
Really small sensing elements



X-ray spectroscopy



Gamma spectroscopy



*Total nuclear decay energy spectroscopy
(for **alpha**, beta, or EC decay)*

3 keV

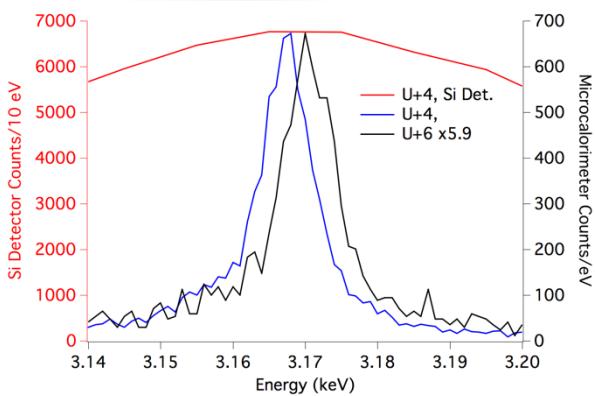
100 keV

5 MeV

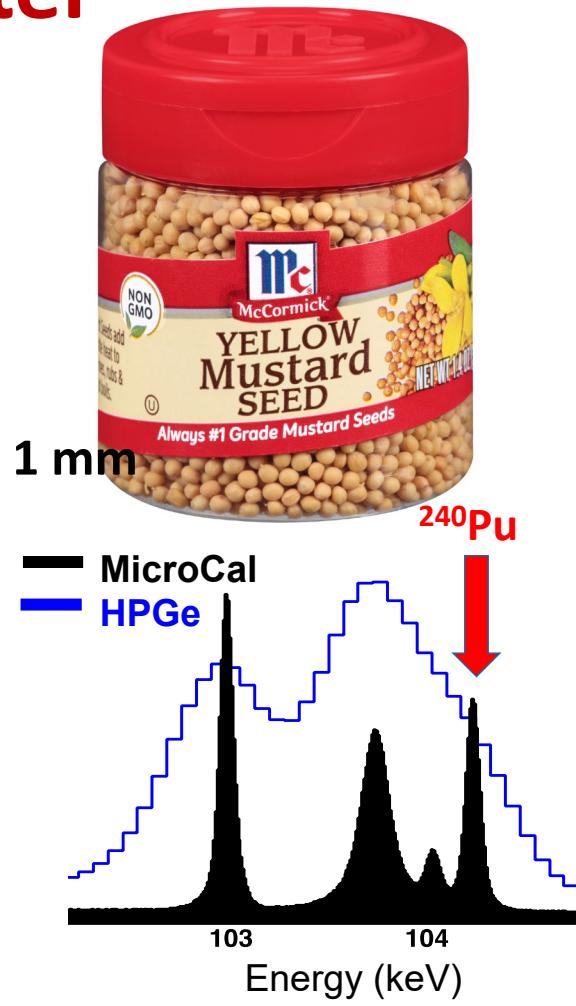
Microcalorimeter



0.3 mm



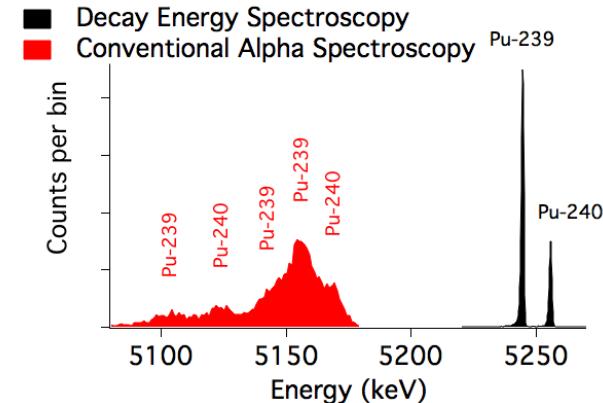
X-ray spectroscopy



Gamma spectroscopy



3 mm



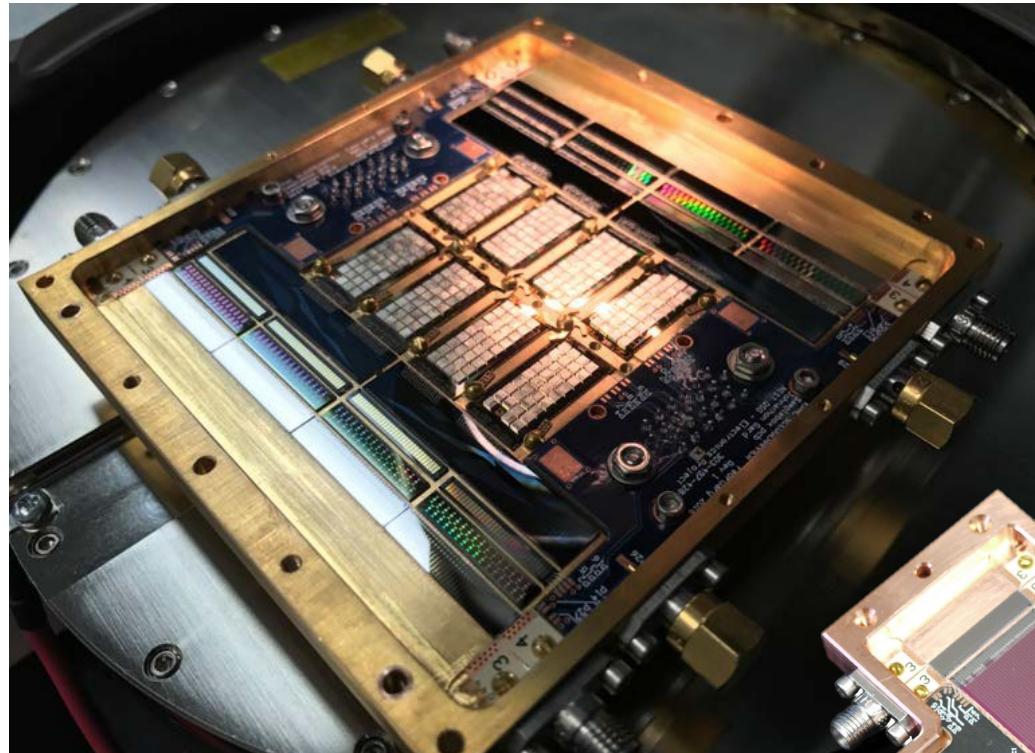
*Total nuclear decay energy spectroscopy
(for **alpha**, beta, or EC decay)*

3 keV

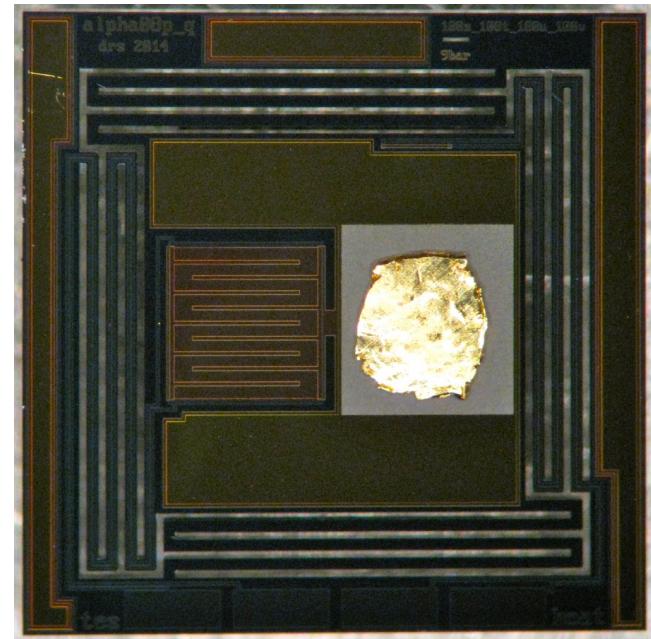
100 keV

5 MeV

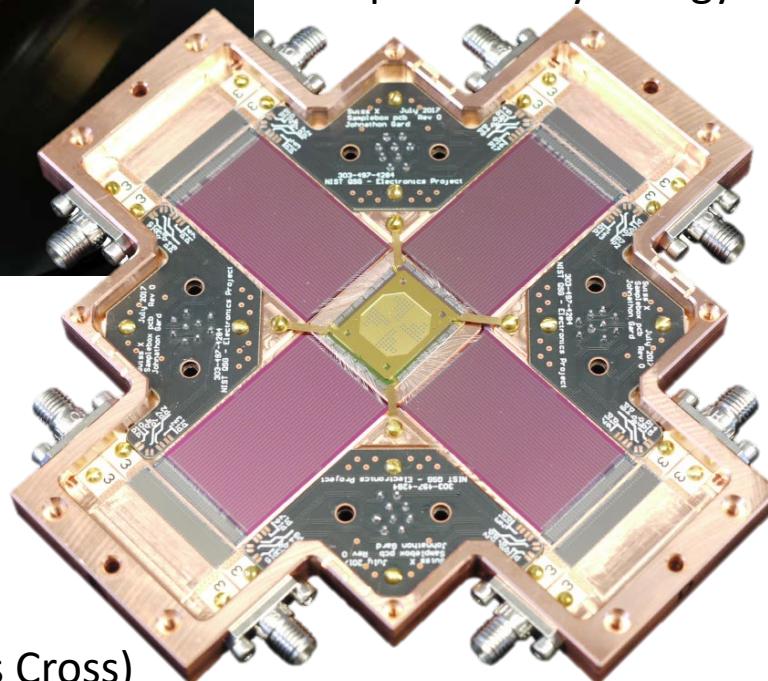
Microcalorimeter



Gamma Array (SLEDGEHAMMER)



“alpha” Decay Energy Spectroscopy



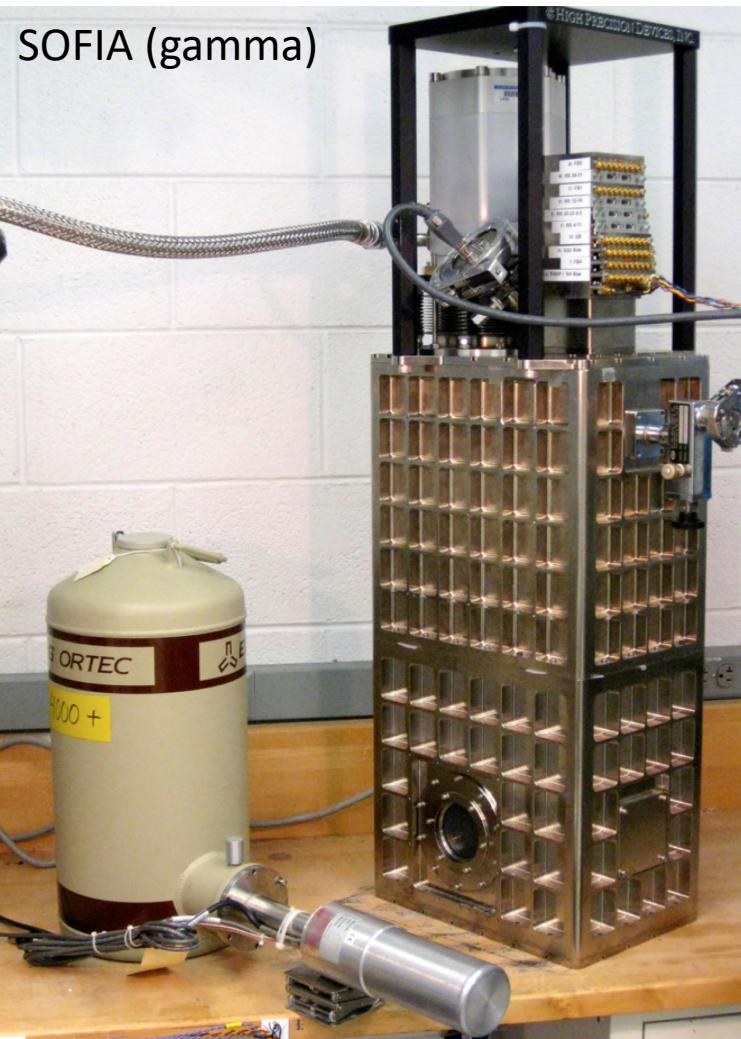
X-ray Array (Swiss Cross)

Cryogen-Free Cryostats

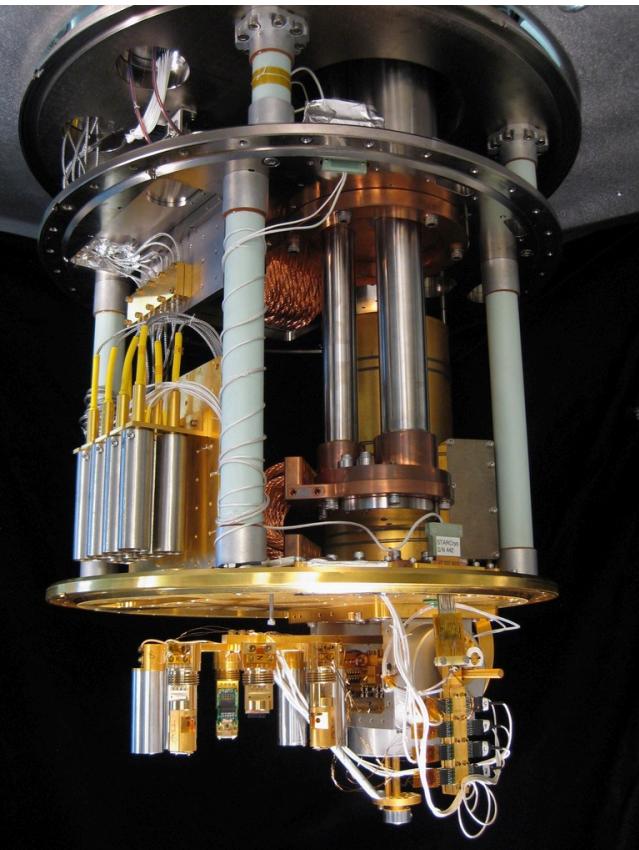
BAYMAX (x-ray)



SOFIA (gamma)

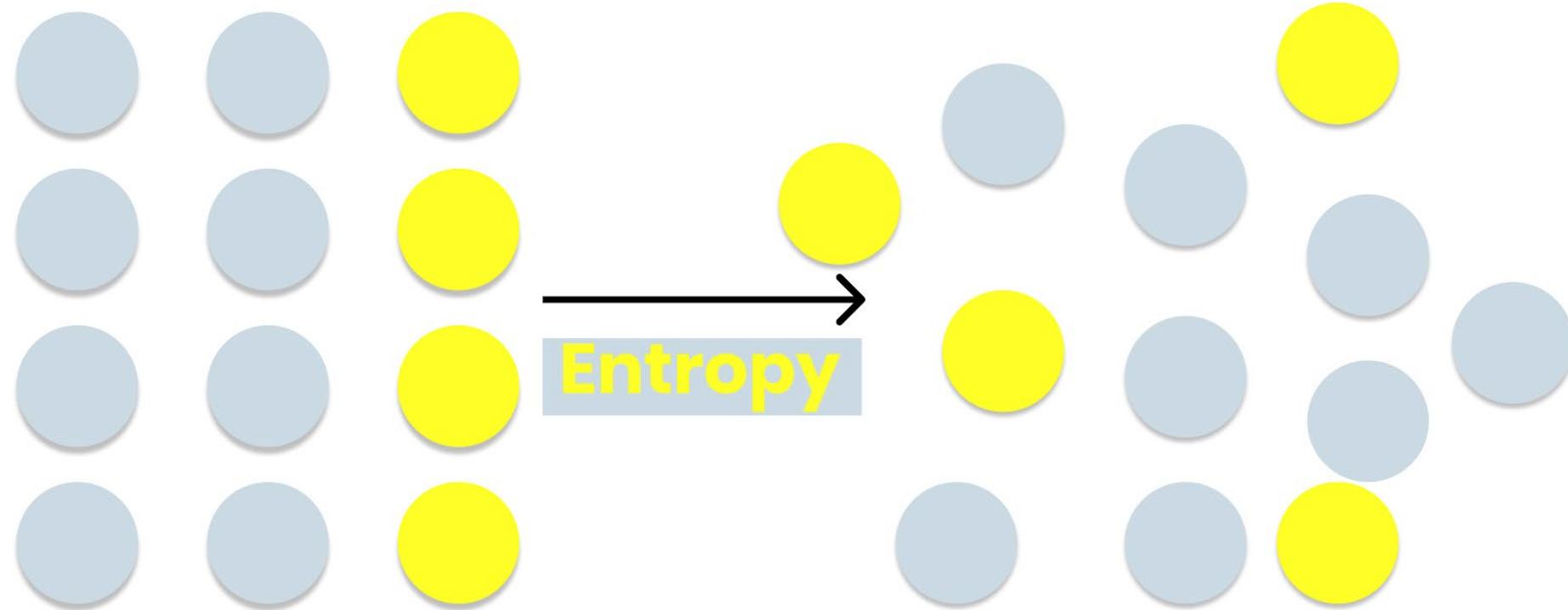


SARAH (DES)

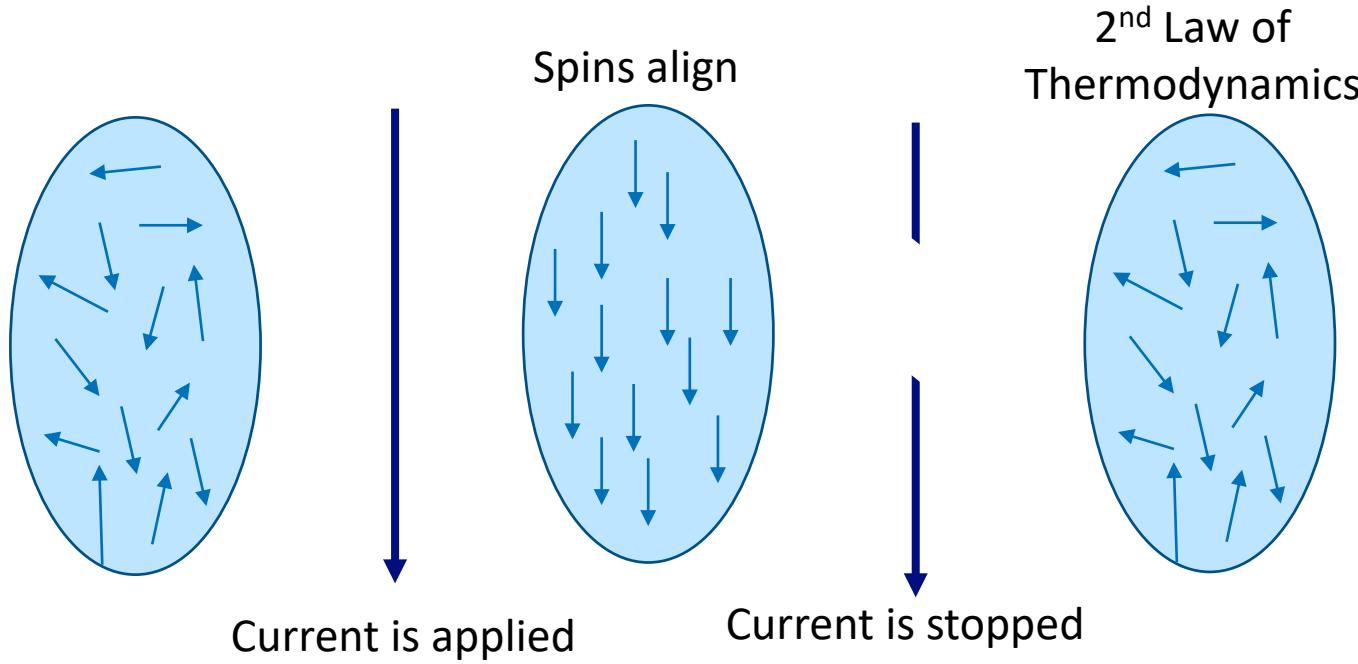


Entropy: The Good Guy Story

2nd Law of
Thermodynamics



Entropy: The Good Guy Story



Low Entropy \longrightarrow High Entropy

Low Energy \longrightarrow High Energy

Steal heat from the system
(i.e. make cryostat cold)

Cryogen-Free Cryostats

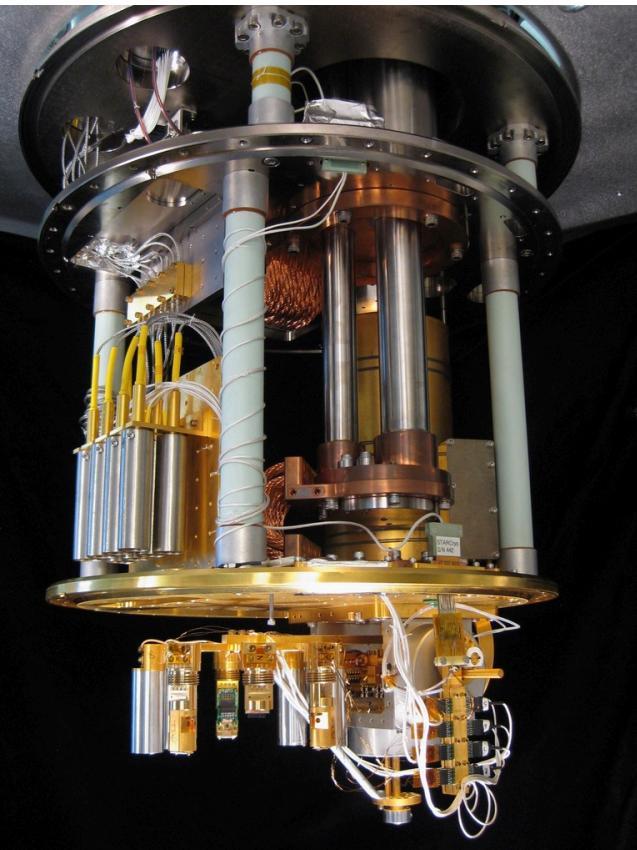
BAYMAX



SOFIA



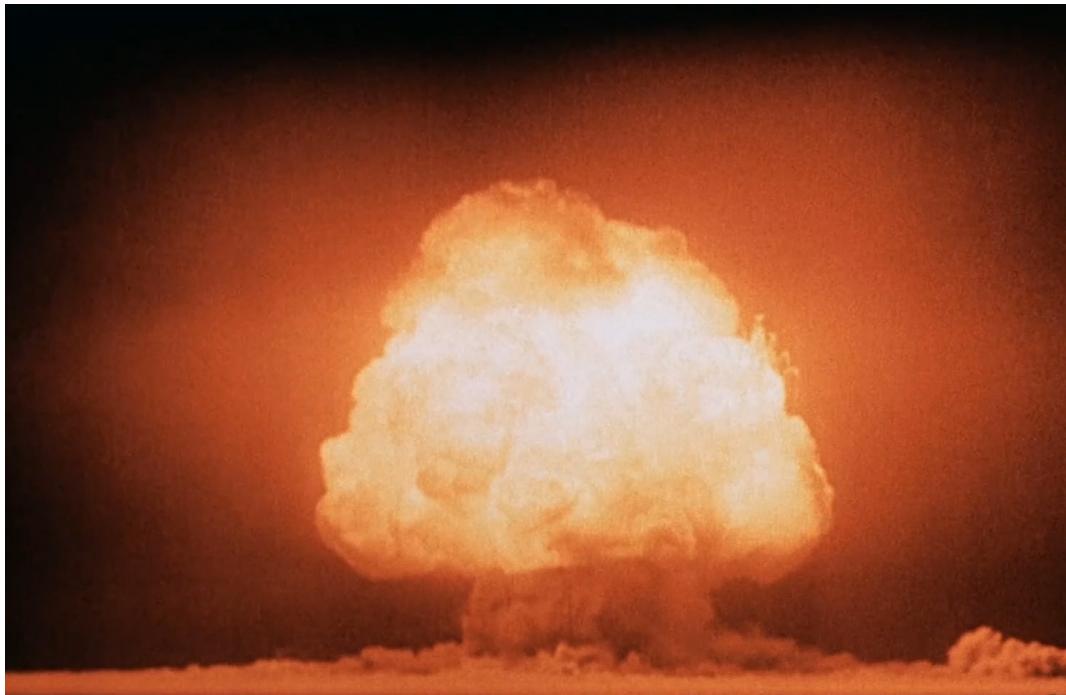
SARAH



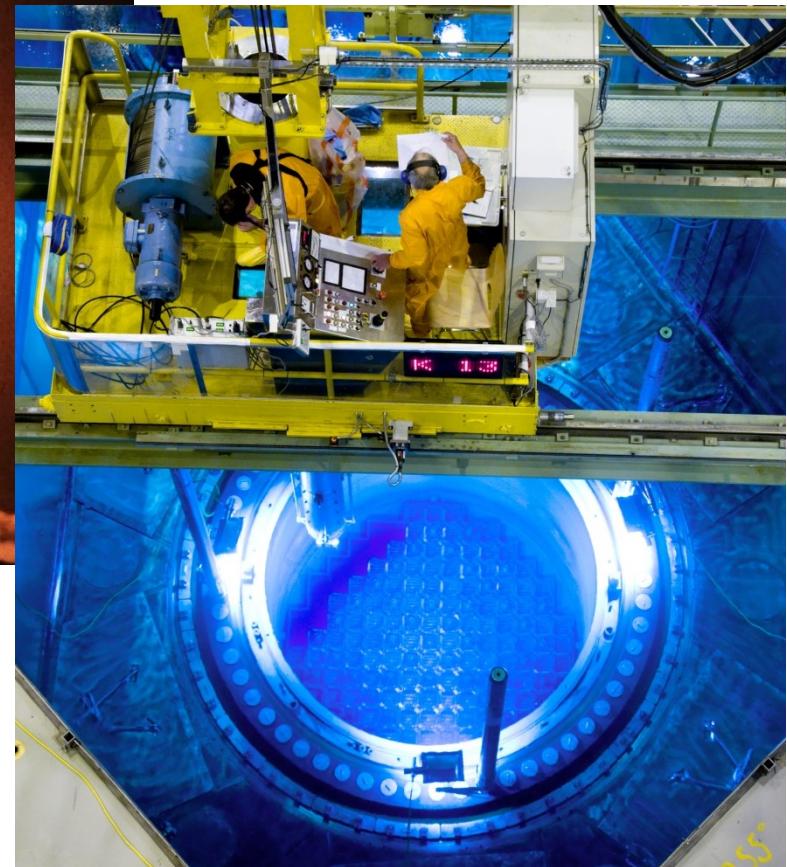
Outline

- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

Nuclear Safeguards

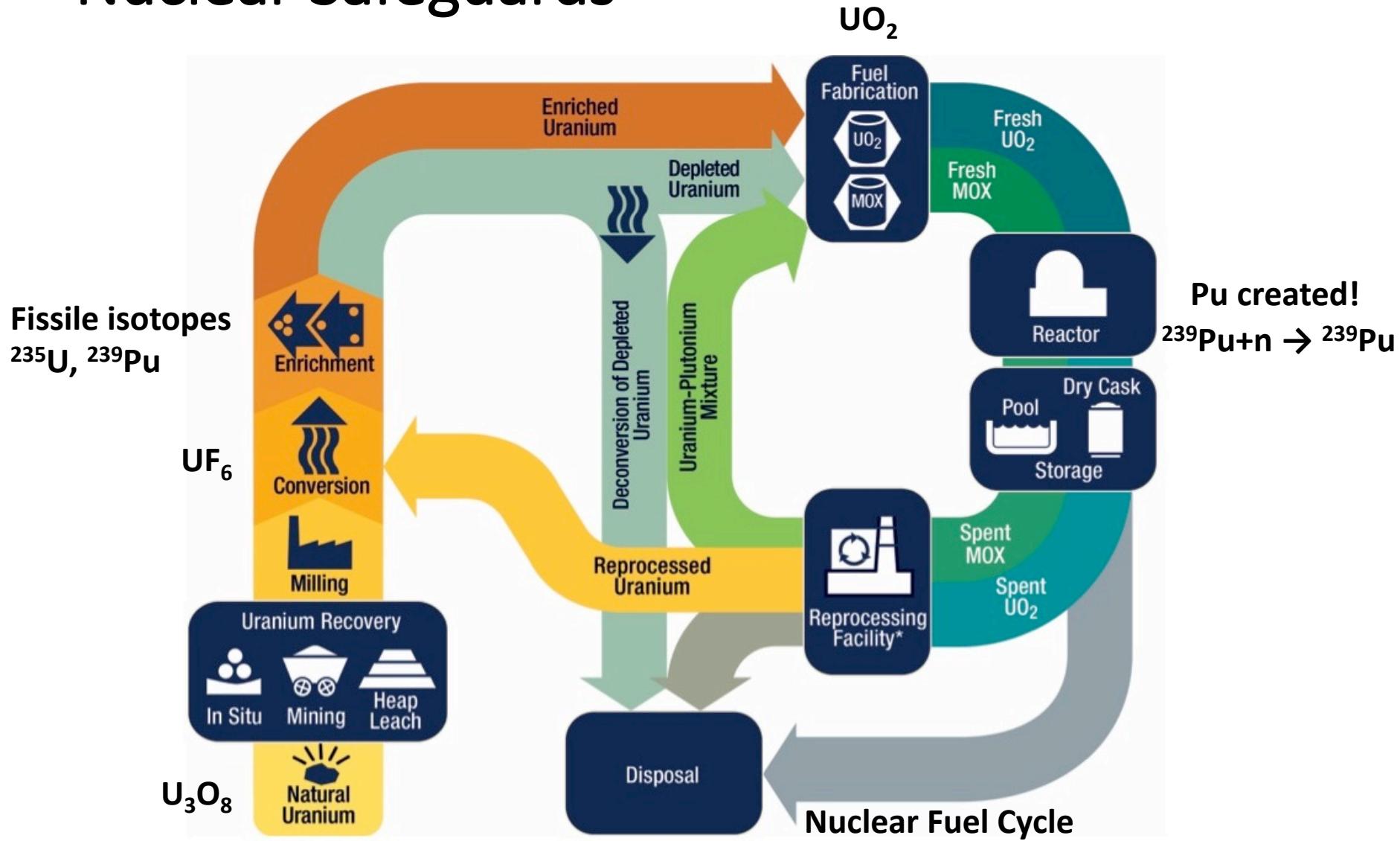


Trinity Test (July 16, 1945)



Nuclear Reactor being refueled

Nuclear Safeguards



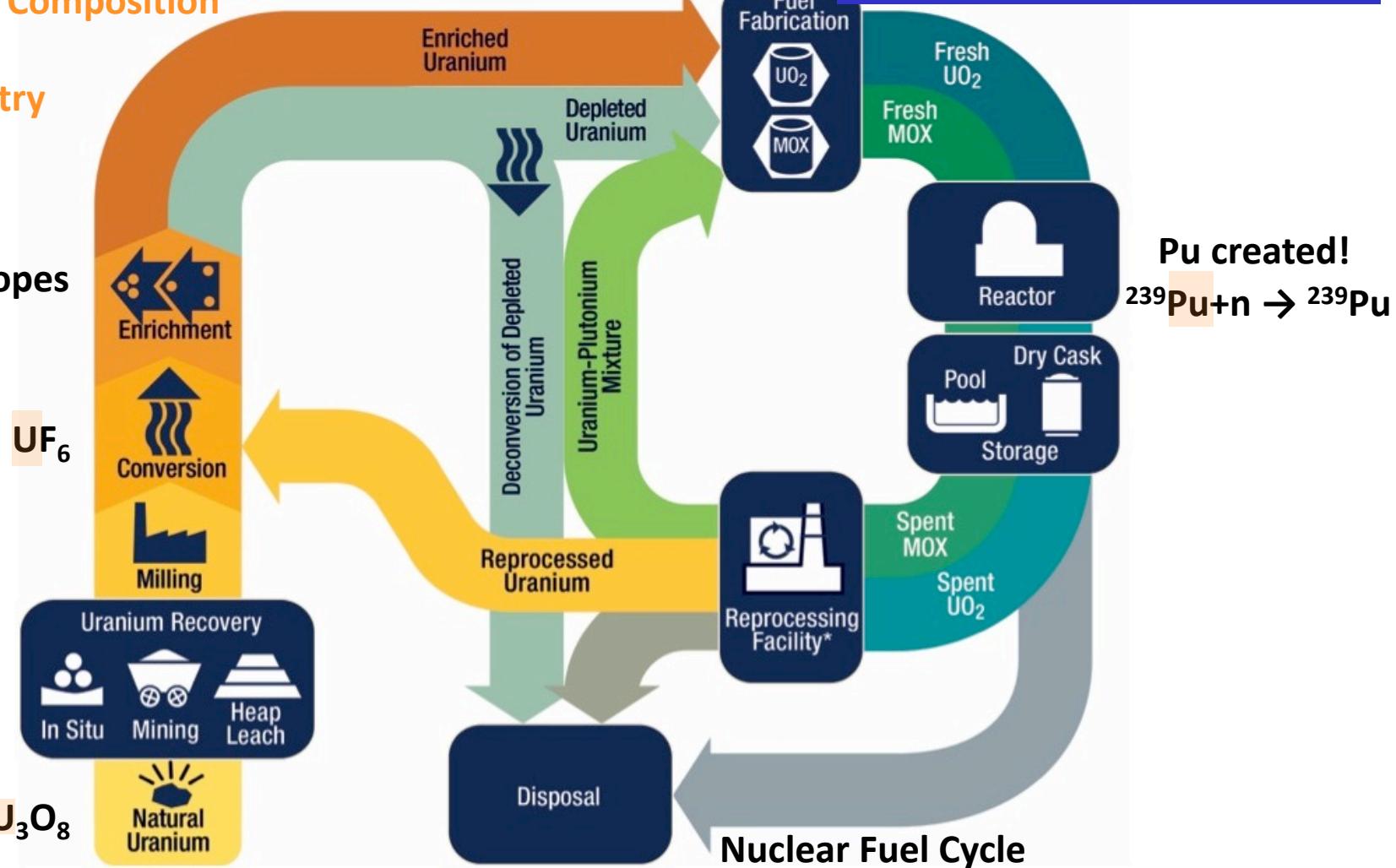
Nuclear Safeguards

Elemental Composition

- X-rays
- Chemistry

Fissile isotopes

^{235}U , ^{239}Pu

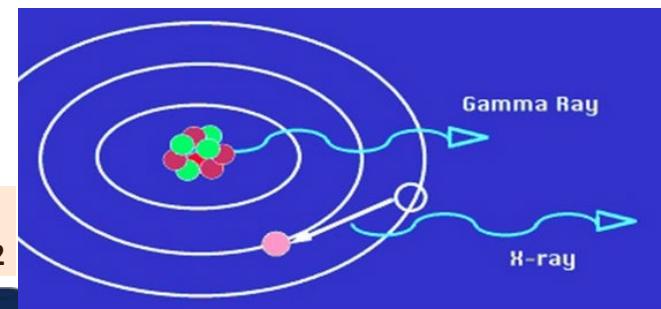


Nuclear Safeguards

Molecular Composition

- Combination of X-rays
- Chemistry

Fissile isotopes
 ^{235}U , ^{239}Pu



Nuclear Fuel Cycle

Nuclear Safeguards

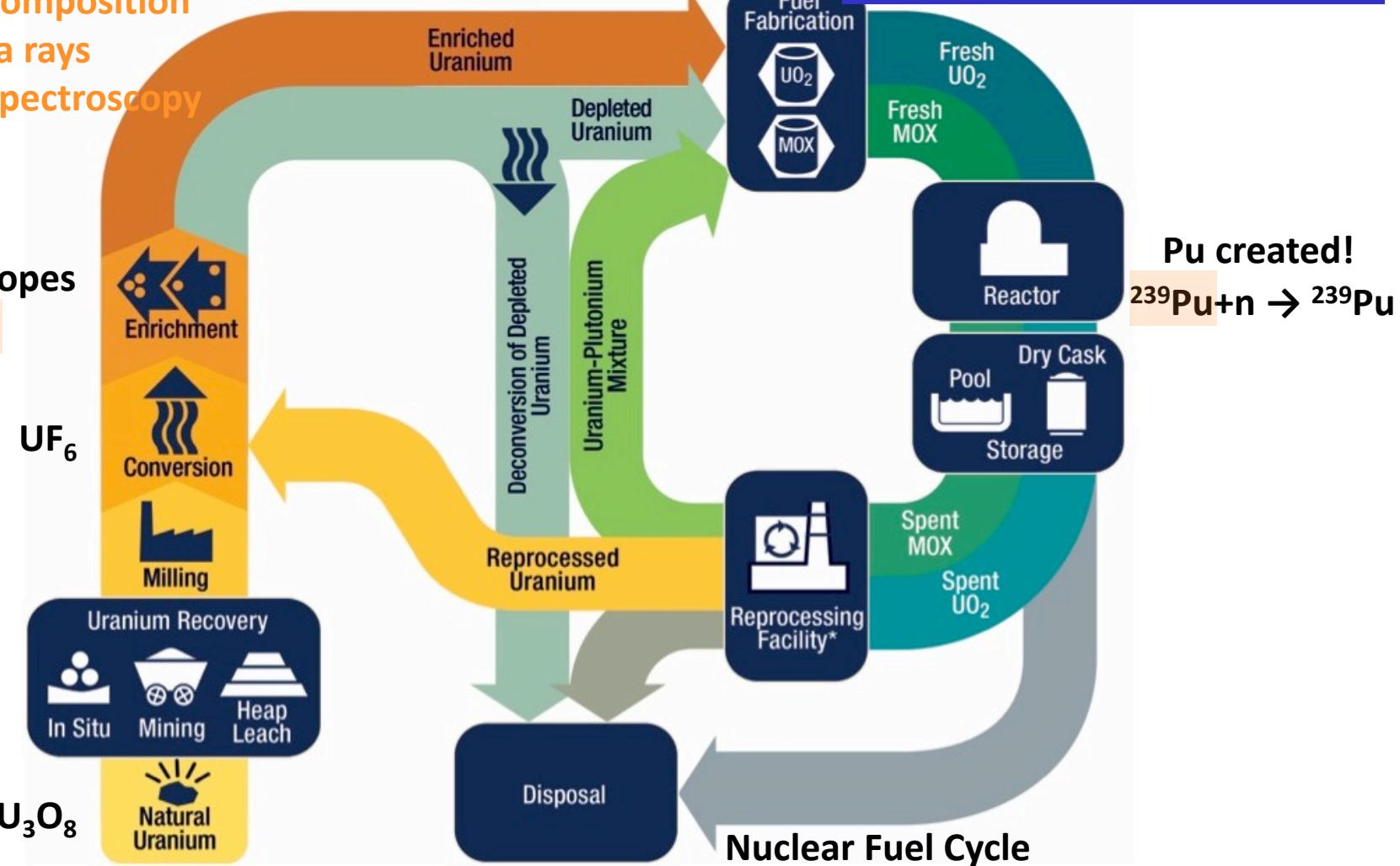
Isotopic Composition

→ Gamma rays

→ Mass Spectroscopy

Fissile isotopes

^{235}U , ^{239}Pu



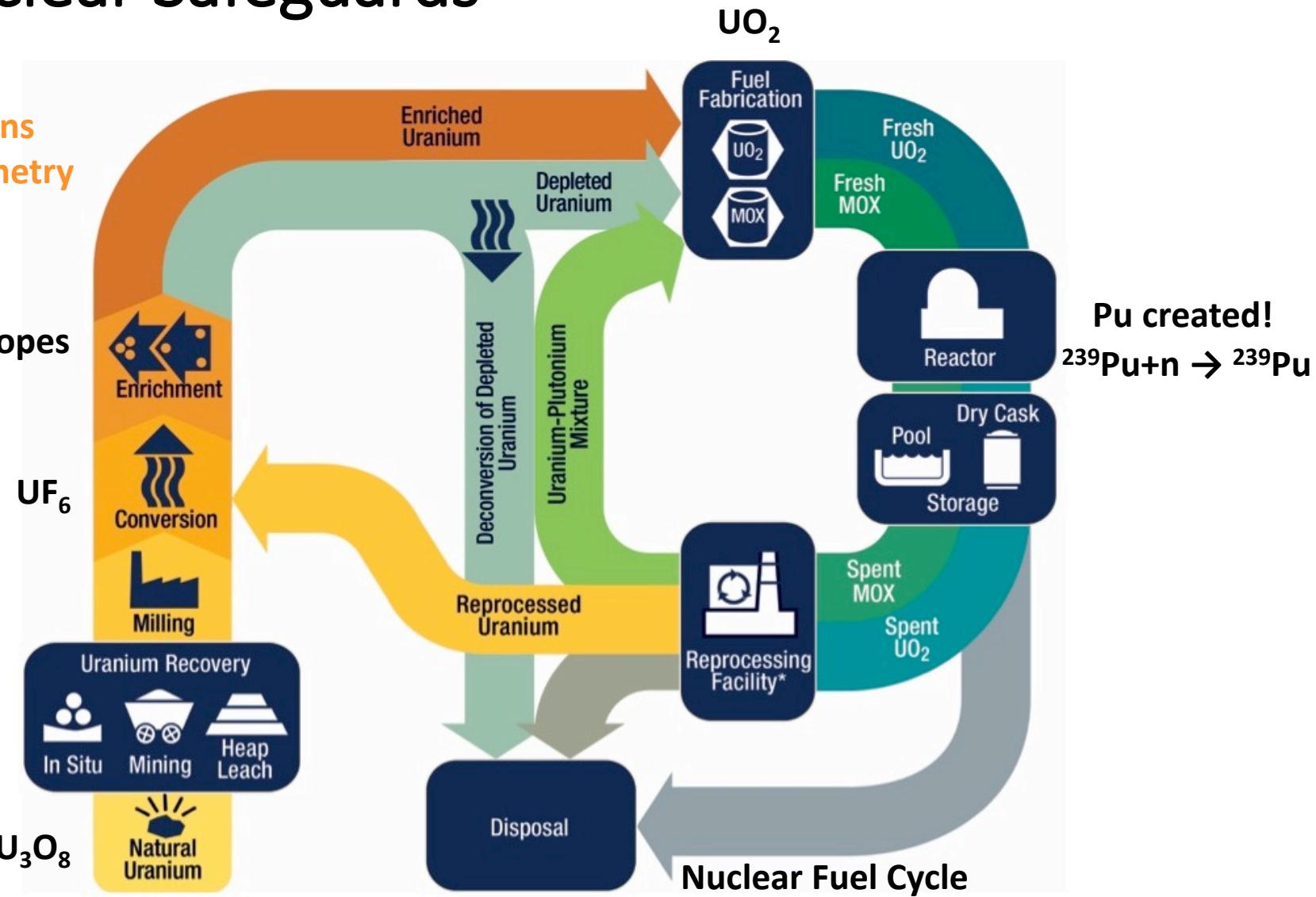
Nuclear Safeguards

Mass

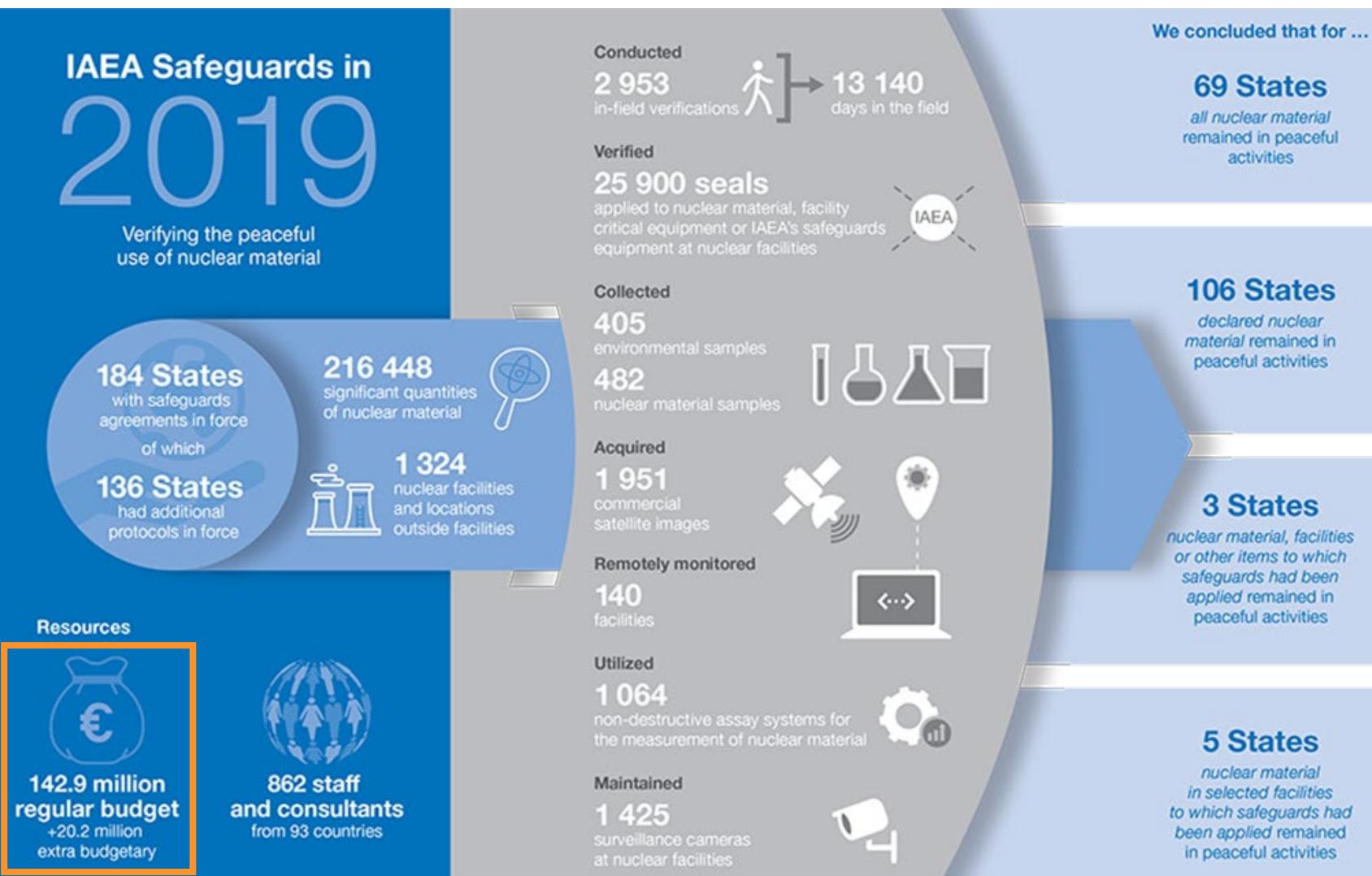
→ Neutrons

→ Calorimetry

Fissile isotopes
 ^{235}U , ^{239}Pu



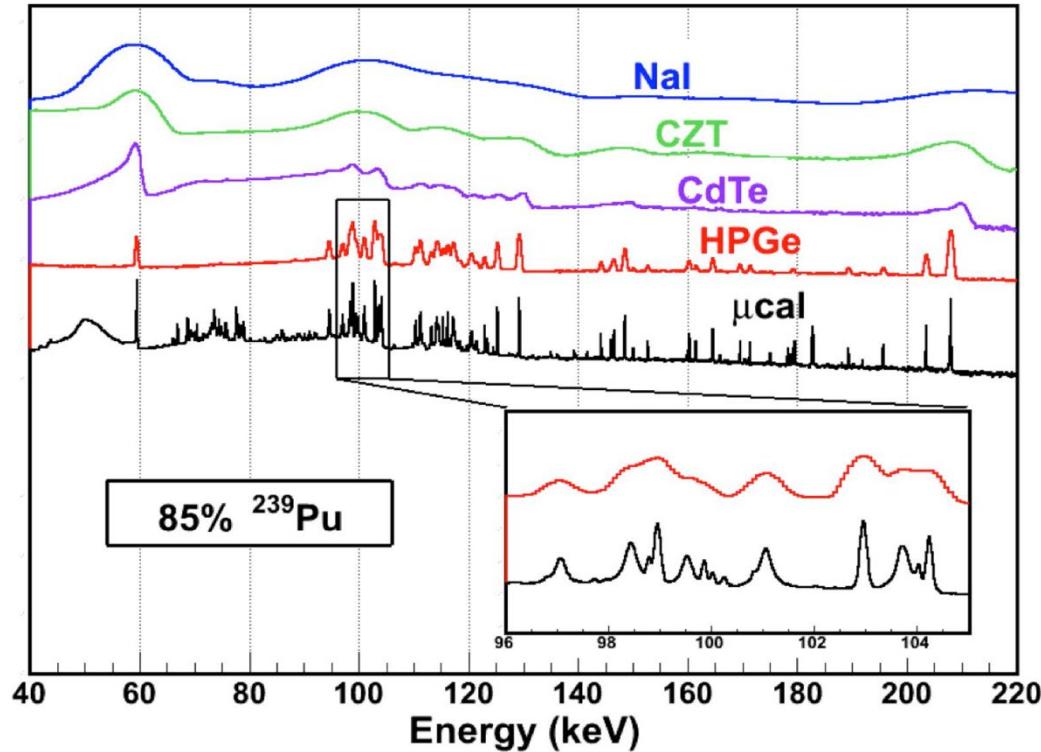
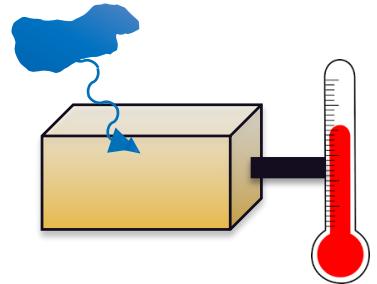
International Atomic Energy Agency



Outline

- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

Gamma Ray Spectroscopy



Applications in safeguards and material accounting:

Plutonium isotopic composition

- Purified U and Pu products
- U/TRU products
- Fresh MOX fuel
- Wastes

Nuclear data for improved HPGe analysis

- X-ray line widths
- Gamma-ray energies
- Gamma-ray branching fractions

Single pixel: 22 eV FWHM (100 keV)

Large array: 50-70 eV FWHM (100 keV)

Planar HPGe: ~530 eV FWHM (100 keV)

Gamma Ray Spectroscopy

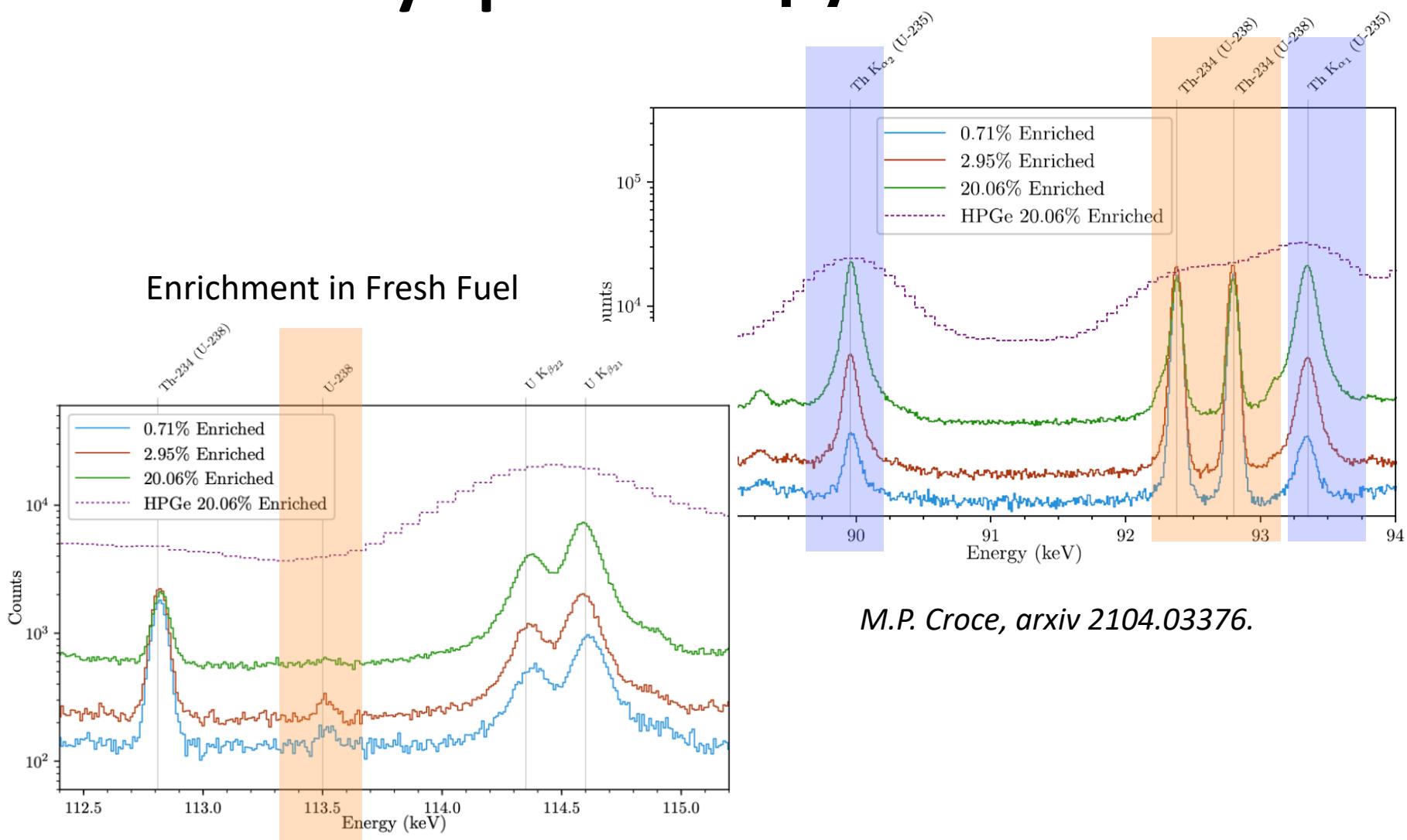


SOFIA:
LANL Pu facility
ORNL measurement tour



INL Spectrometer to be permanently installed in Analytical Laboratory

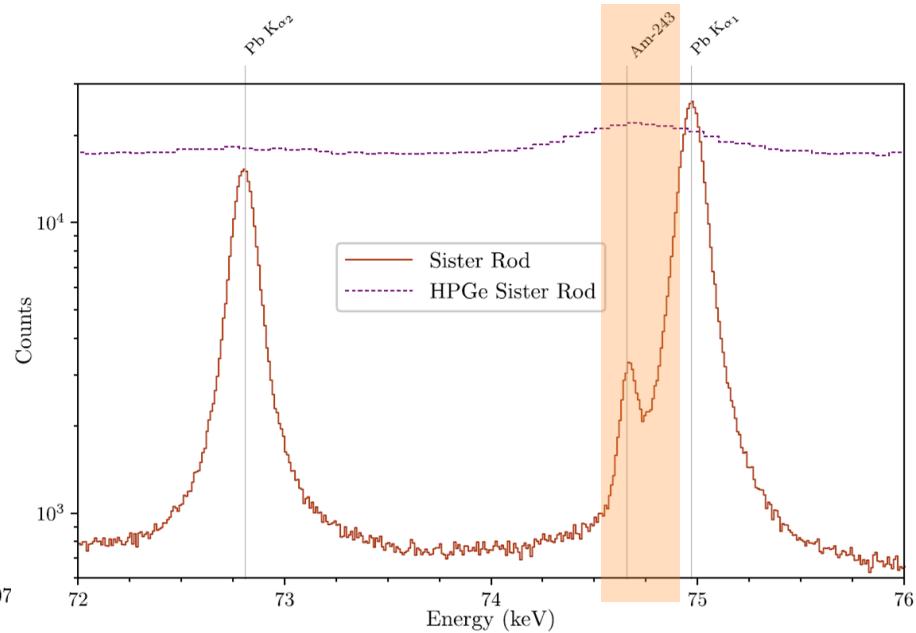
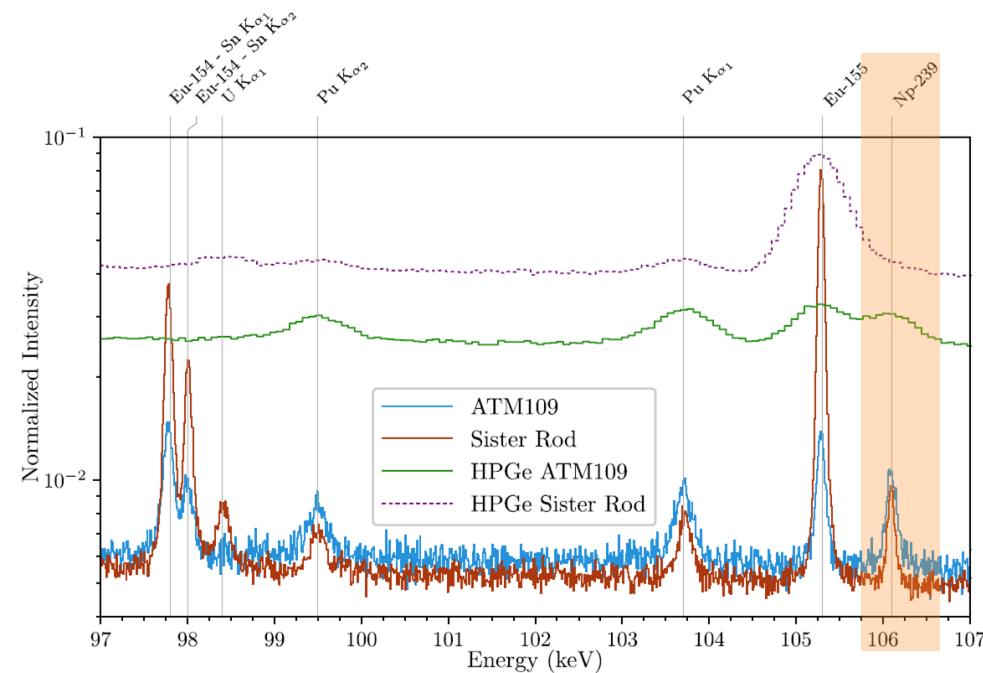
Gamma Ray Spectroscopy



M.P. Croce, arxiv 2104.03376.

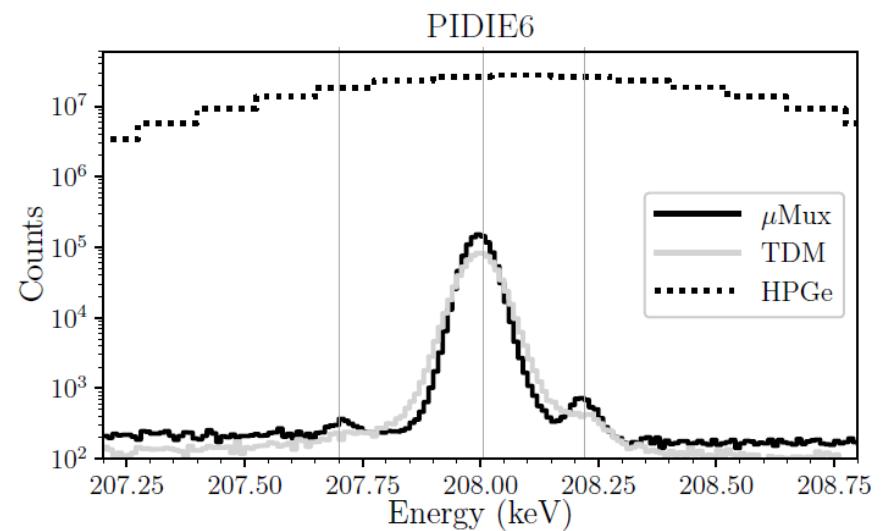
Gamma Ray Spectroscopy

Spent Fuel



M.P. Croce, arxiv 2104.03376.

Gamma Ray Spectroscopy



K.E. Koehler, arxiv 2103.15893

Improved nuclear data



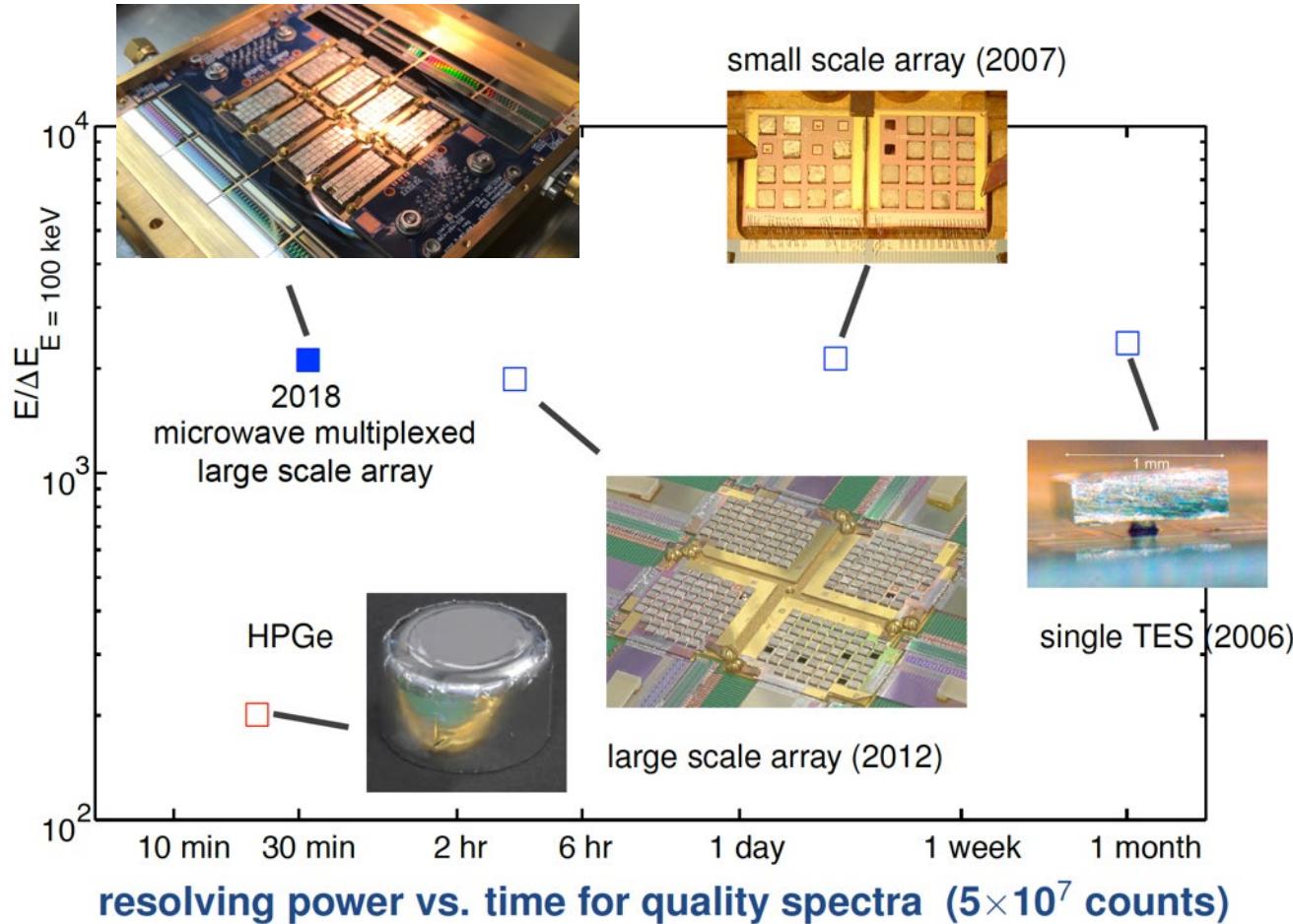
Improved HPGe analysis

Energy [keV]	Isotope	NNDC BR	μ_{BR}	This work BR	μ_{BR}	μ_{BR}	Agreement
125.21	^{239}Pu	5.63×10^{-5}	2.7	5.51×10^{-5}	13	-0.2	
125.3	^{241}Am	4.08×10^{-3}	2.5	4.08×10^{-3}	1.0	0.0	
144.201	^{239}Pu	2.83×10^{-4}	2.1	2.87×10^{-4}	1.0	0.6	
146.094	^{239}Pu	1.19×10^{-4}	2.5	1.22×10^{-4}	1.4	0.7	
146.55	^{241}Am	4.61×10^{-4}	2.6	4.75×10^{-4}	0.75	1.2	
150.04	^{241}Am	7.40×10^{-5}	3.0	7.76×10^{-5}	1.3	1.5	
152.72	^{238}Pu	9.29×10^{-4}	0.75	9.46×10^{-4}	0.78	1.7	
159.955	^{241}Pu	6.68×10^{-6}	1.1	6.87×10^{-6}	2.0	1.2	
160.19	^{239}Pu	6.20×10^{-6}	19	5.82×10^{-7}	331	-2.5	
161.45	^{239}Pu	1.23×10^{-4}	1.6	1.20×10^{-4}	1.6	-1.1	
161.54	^{241}Am	1.50×10^{-6}	20.0	3.52×10^{-6}	19.9	2.7	
164.61	^{241}Pu	4.56×10^{-5}	1.6	4.46×10^{-5}	2.0	-0.9	
164.69	^{241}Am	6.67×10^{-5}	3.7	7.78×10^{-5}	4.9	2.4	
169.56	^{241}Am	1.73×10^{-4}	2.3	1.72×10^{-4}	0.9	-0.3	
171.393	^{239}Pu	1.10×10^{-4}	1.8	1.12×10^{-4}	1.4	0.9	
175.07	^{241}Am	1.82×10^{-5}	5.5	1.85×10^{-5}	2.8	0.3	
188.23	^{239}Pu	1.09×10^{-5}	10	8.63×10^{-6}	10.8	-1.6	
189.36	^{239}Pu	8.30×10^{-5}	1.2	7.91×10^{-5}	1.4	-2.6	
191.96	^{241}Am	2.16×10^{-5}	4.6	2.01×10^{-5}	2.8	-1.3	
208.005	^{241}Pu	5.19×10^{-4}	1.4	5.34×10^{-4}	1.9	1.2	
208.01	^{241}Am	7.91×10^{-4}	2.4	8.08×10^{-4}	5.4	0.4	

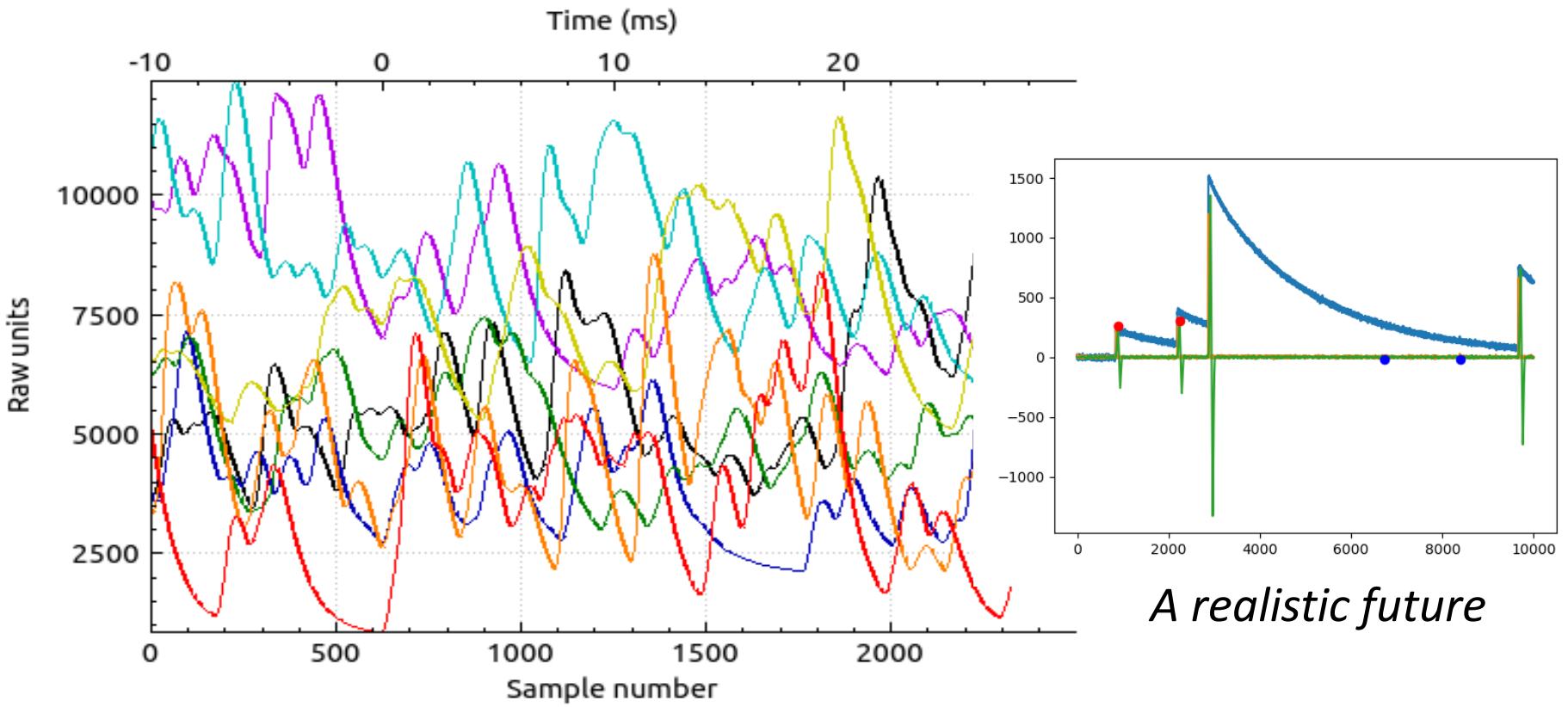
M.D. Yoho, NIM A, 2020.

A Bright Future

Scalable, high-throughput architecture based on microwave frequency-division multiplexing



A Bold Future

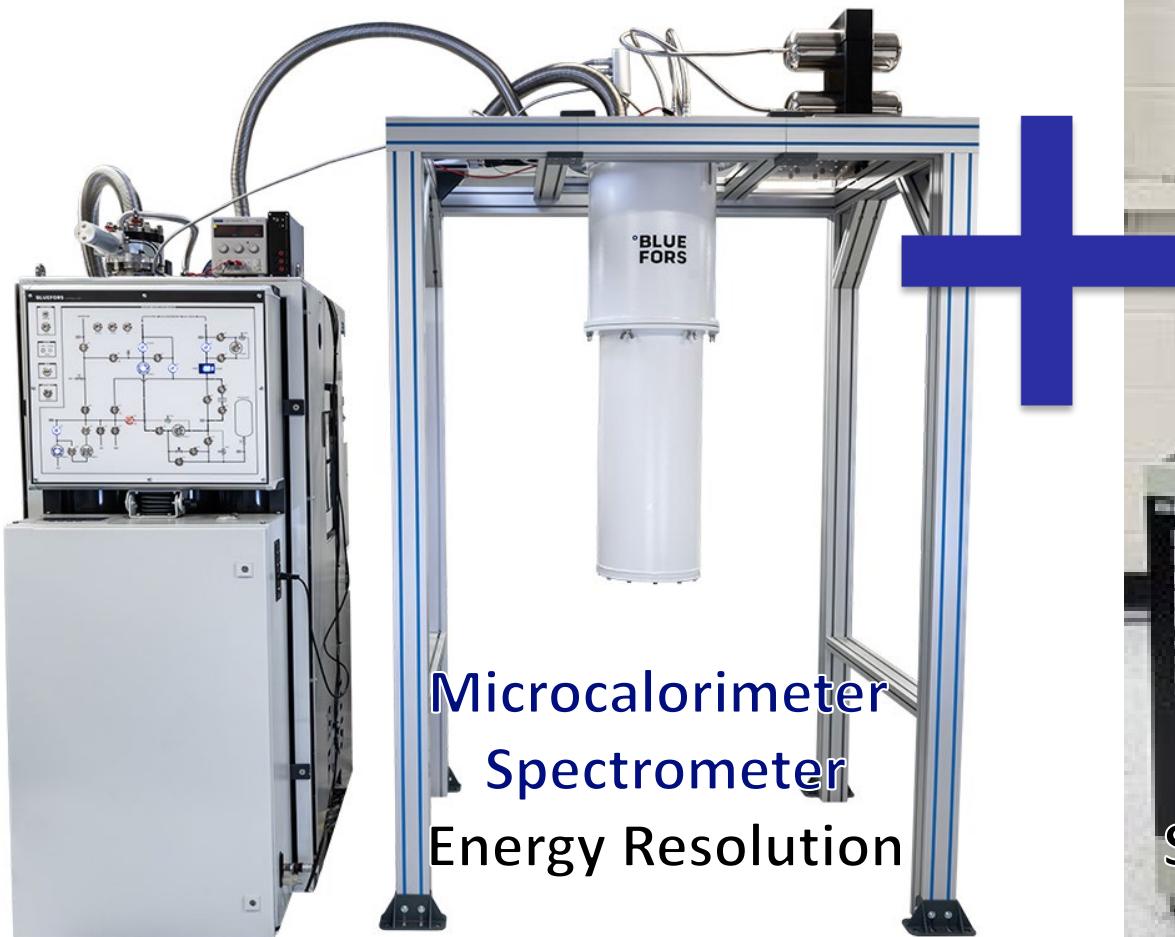


Stable readout even with extreme pulse pileup

Outline

- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

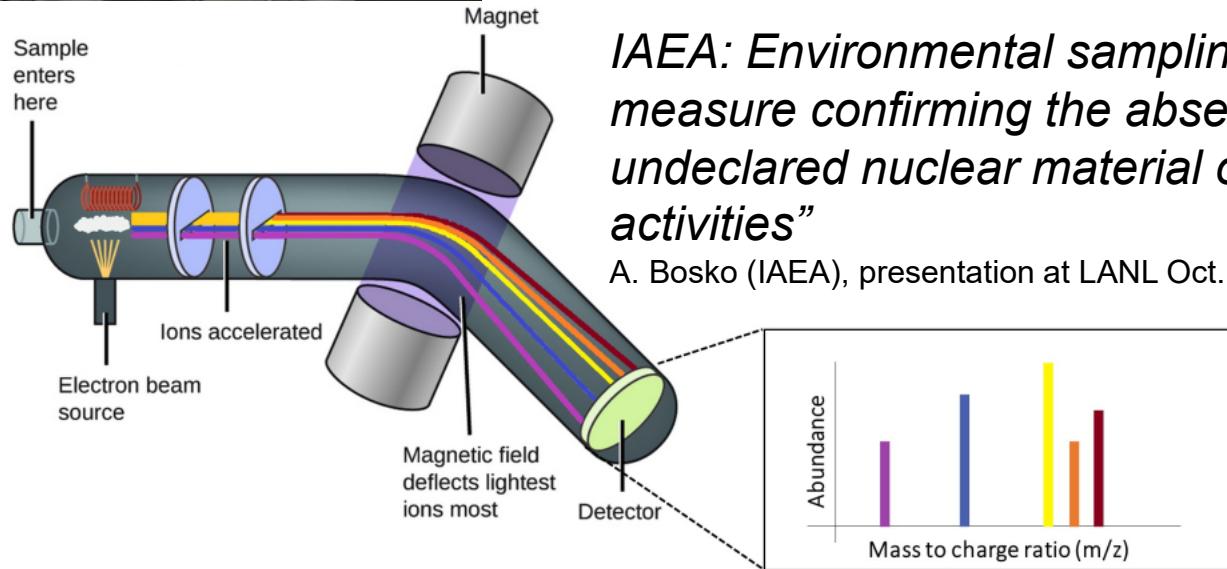
Hyperspectral X-ray Imaging



Hyperspectral X-ray Imaging



Hyperspectral X-ray Imaging

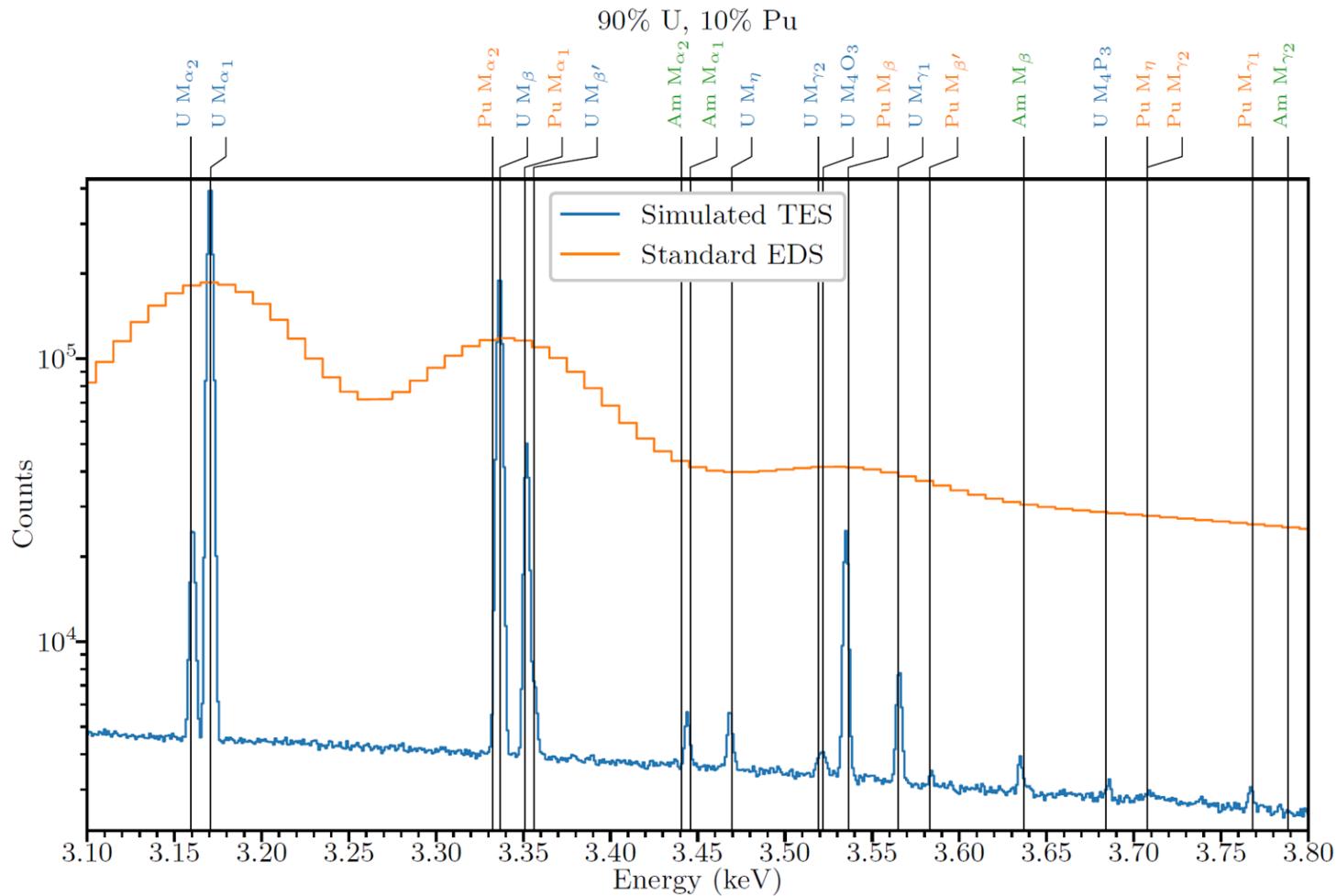


IAEA: Environmental sampling is “the measure confirming the absence of undeclared nuclear material or nuclear activities”

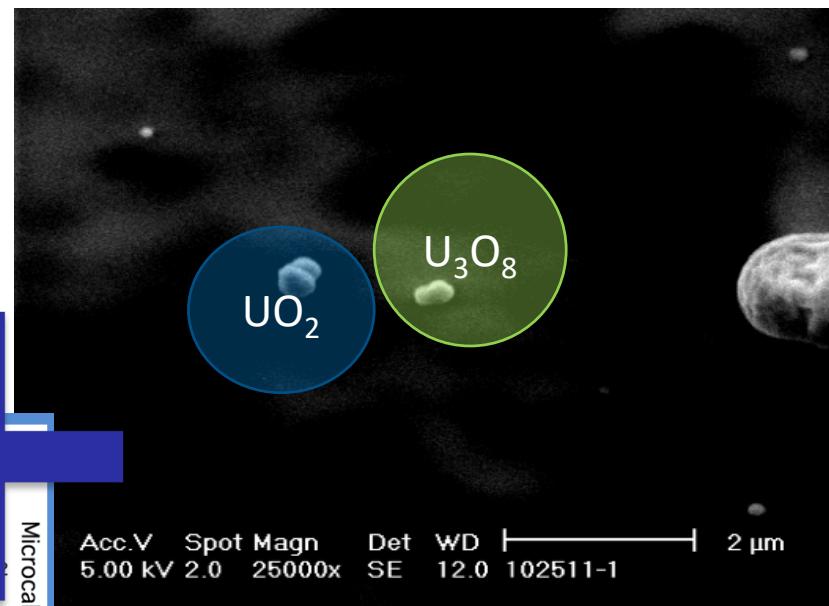
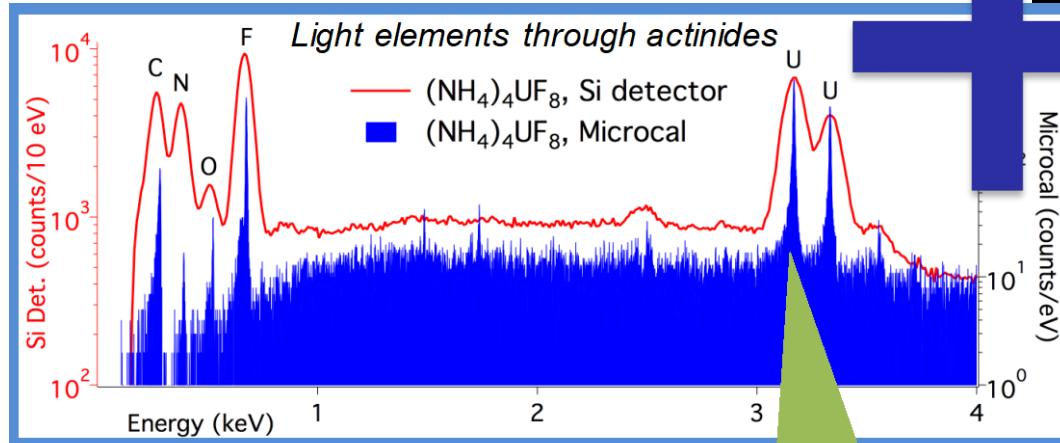
A. Bosko (IAEA), presentation at LANL Oct. 15, 2019

Hyperspectral X-ray Imaging

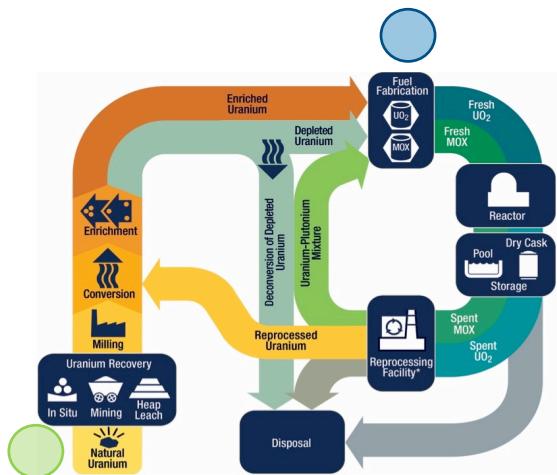
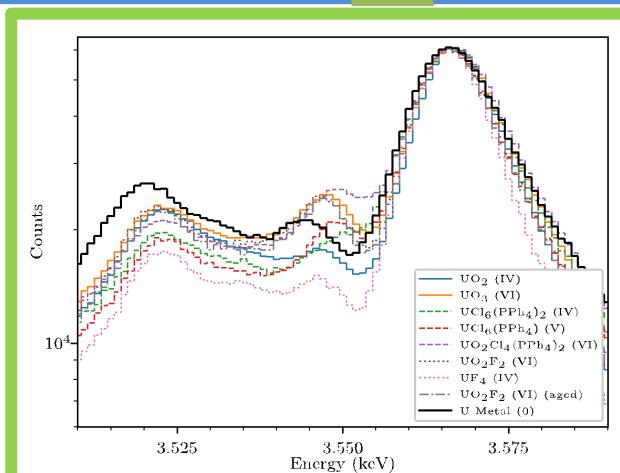
- High resolution, ~6 eV, can resolve U and Pu peaks and measure their ratios
- Decrease the detection limit for trace elements



Hyperspectral X-ray Imaging

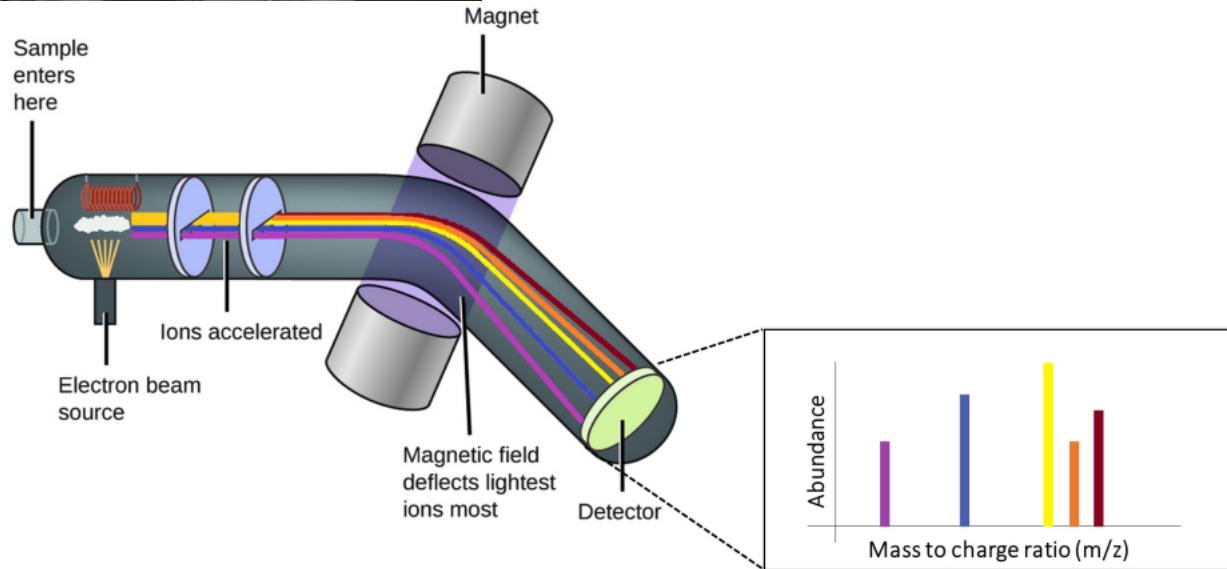


Hydrolyzed UF_6



M.H. Carpenter, JLTP 2020.

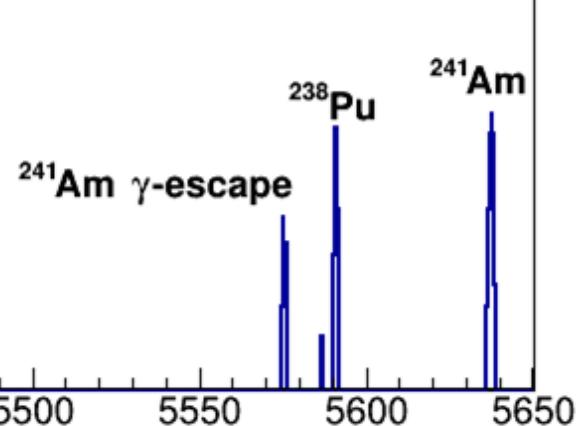
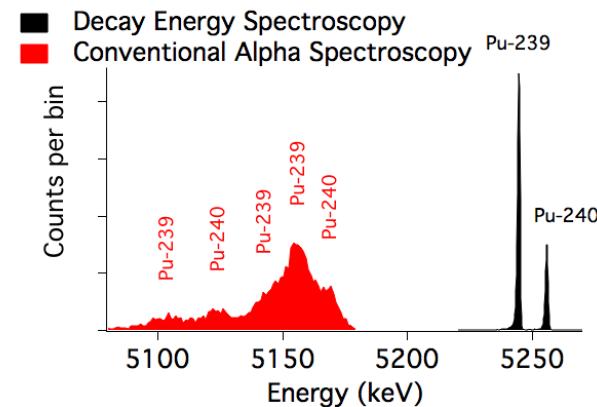
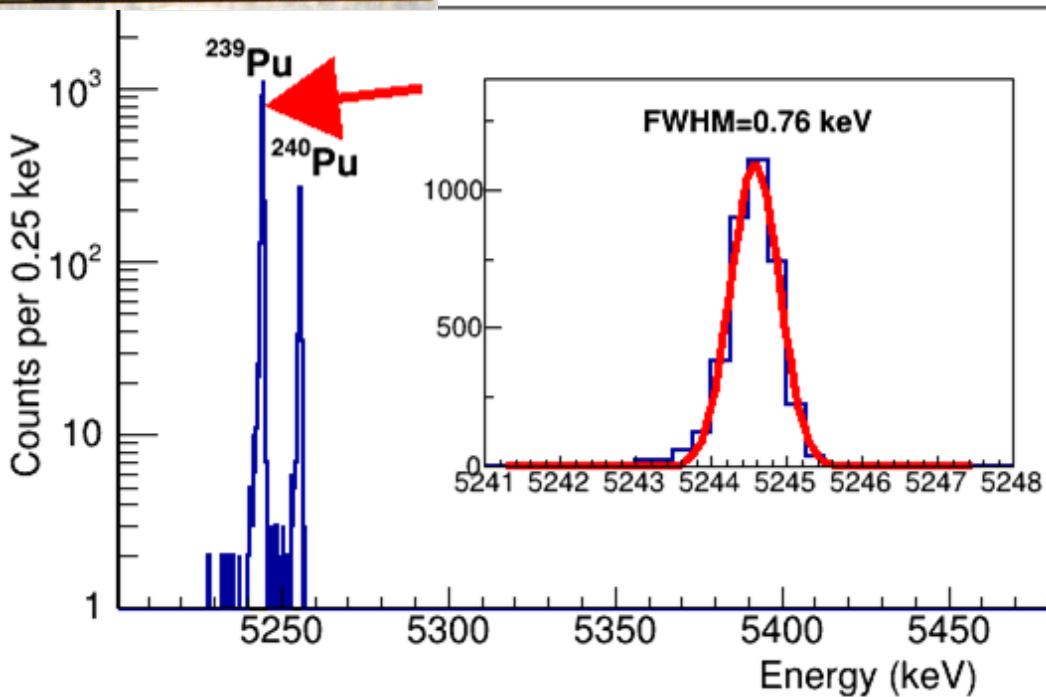
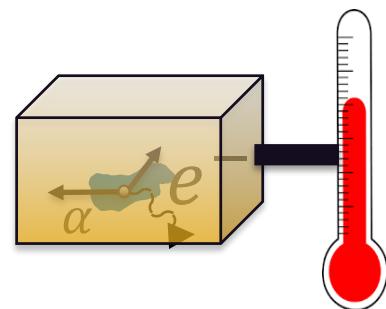
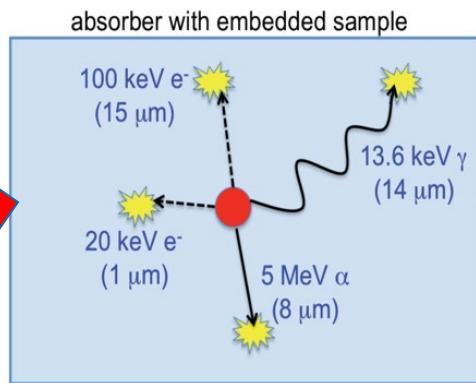
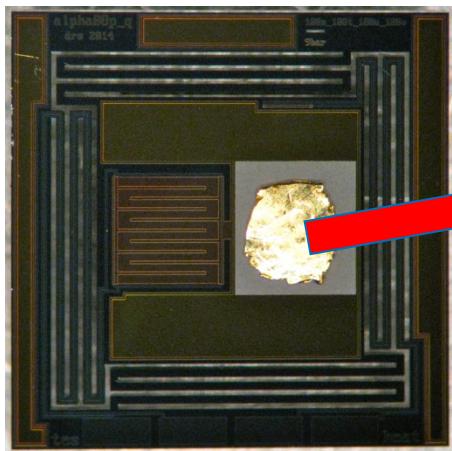
Hyperspectral X-ray Imaging



Outline

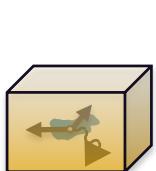
- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

Decay Energy Spectroscopy

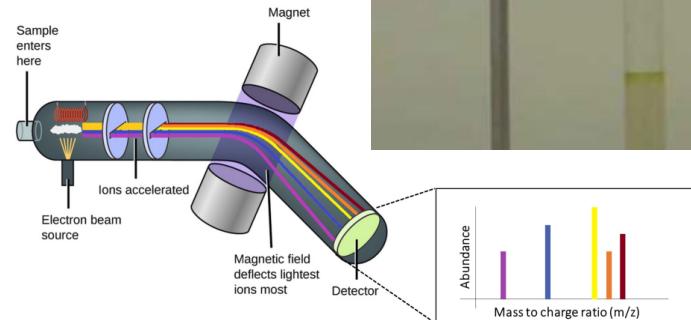


A. Hoover, Anal. Chem. 2015.

Decay Energy Spectroscopy



x 15 =



Advantages

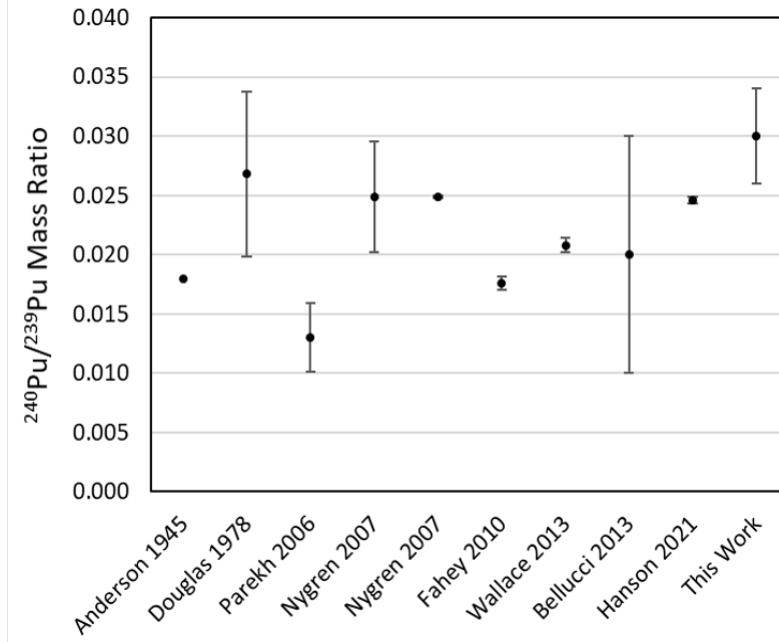
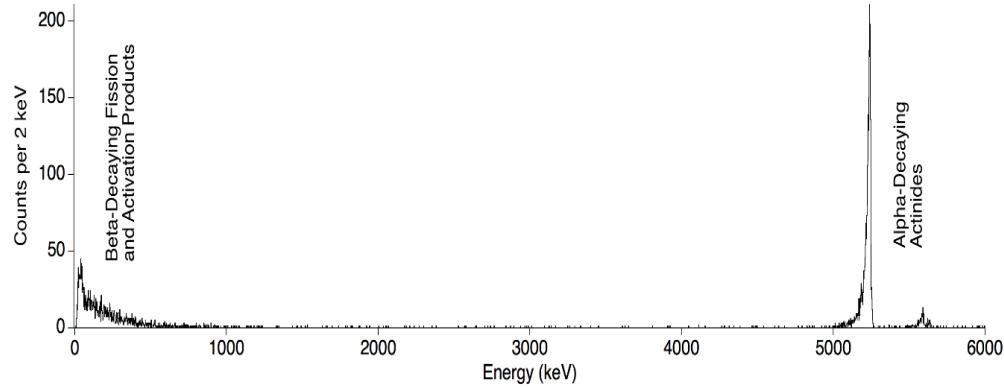
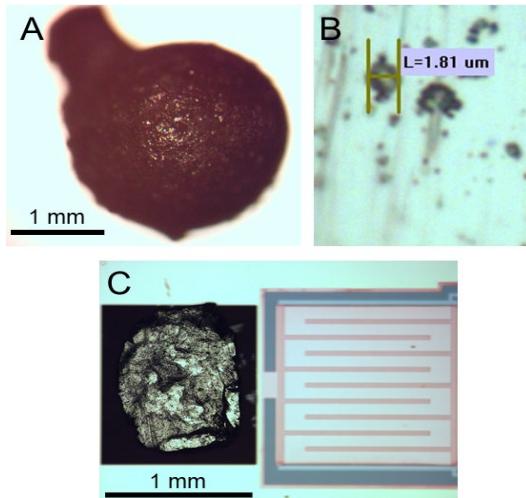
- Low activities
→ Easy to transport
- Simplified spectra
→ Easy to analyze
- Multiple isotopes at once
→ No chemistry
- Minimal sample preparation
(compared to mass spec)
→ No chemistry



Decay Energy Spectroscopy – Nuclear Forensics

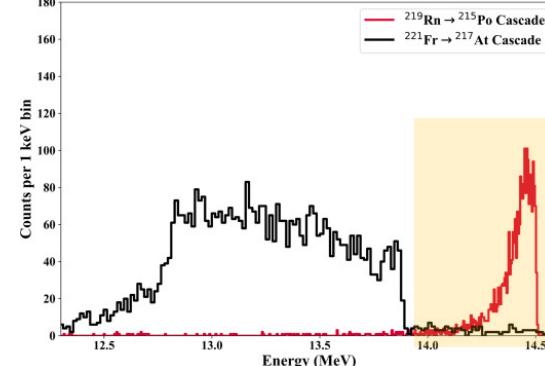
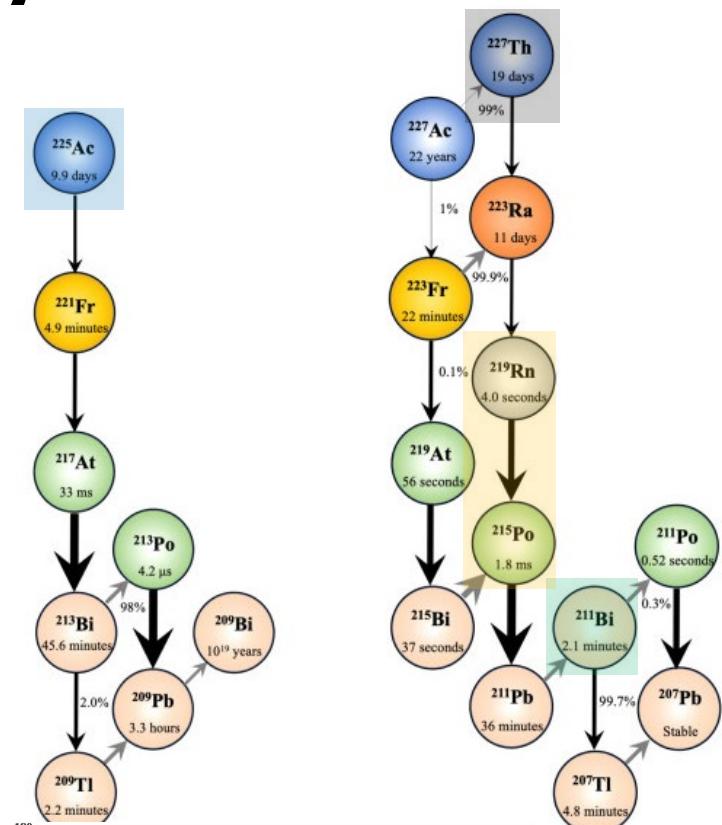
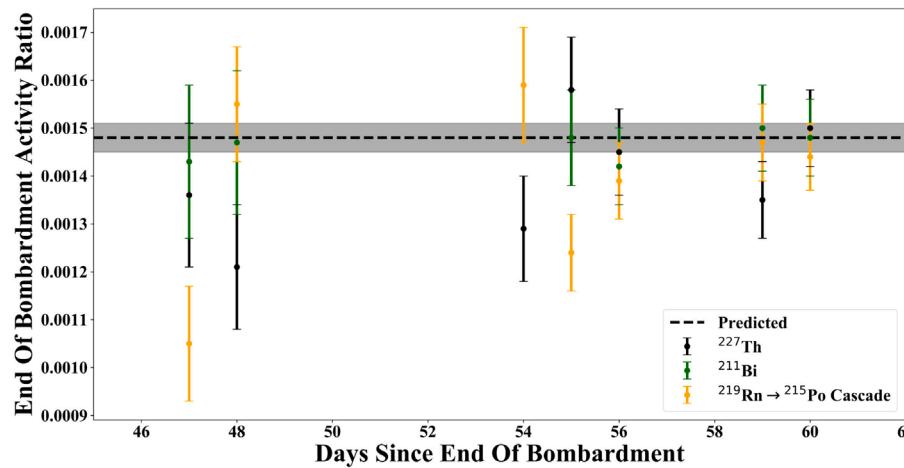
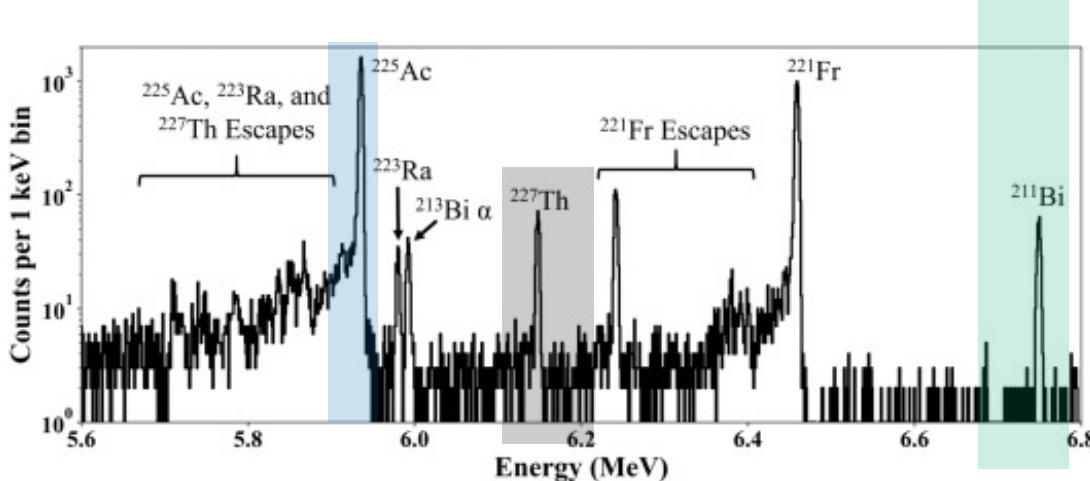


M.P. Croce, arxiv 2103.12215
D.J. Mercer, arxiv 2103.06240

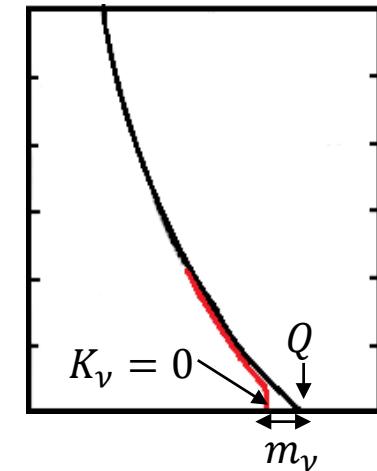
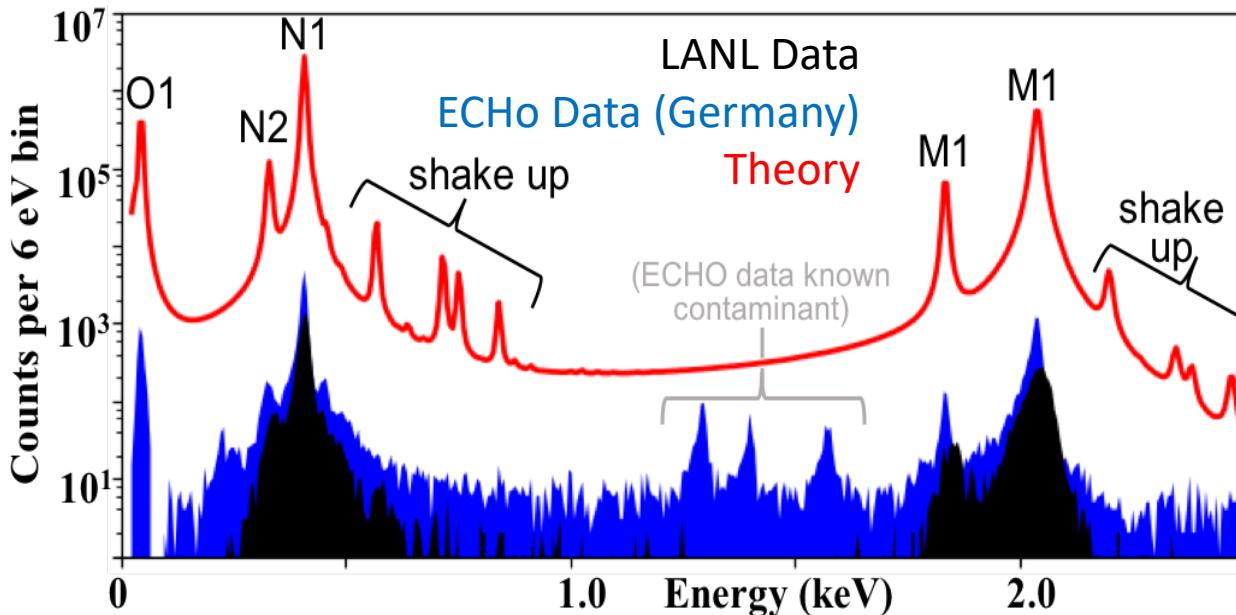
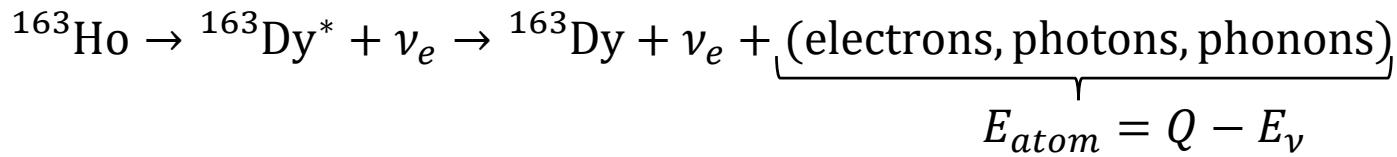


Decay Energy Spectroscopy – Cancer Research

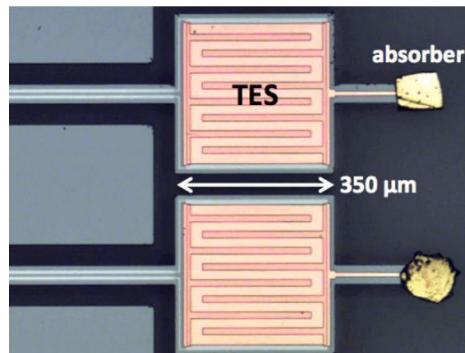
^{225}Ac and ^{227}Ac



Decay Energy Spectroscopy – Neutrino Physics



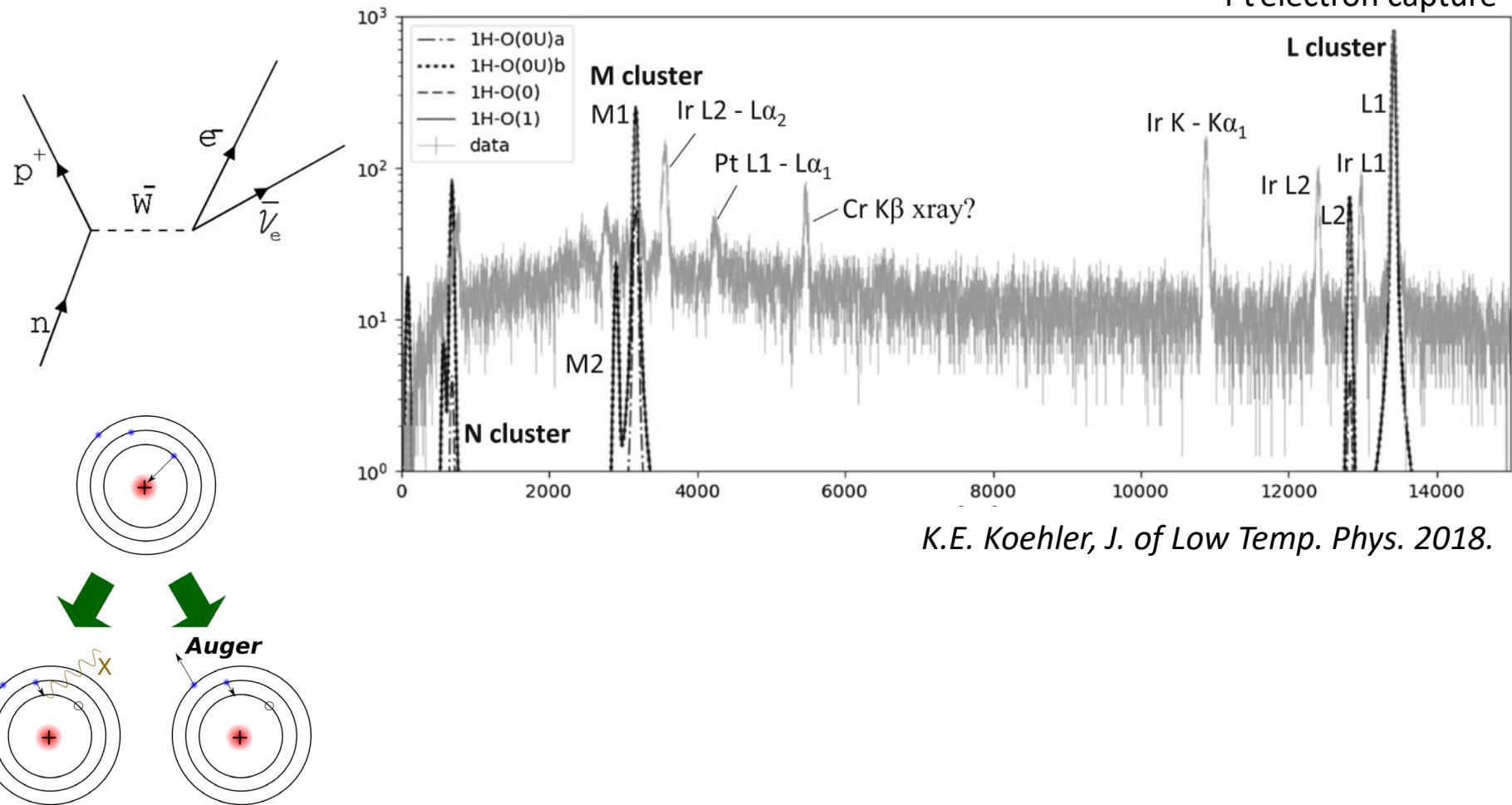
M.P. Croce, J. of Low
Temp. Phys., 2016.



The endpoint region is most sensitive to the neutrino mass.

Decay Energy Spectroscopy

Intersection of Nuclear and Atomic Theory



K.E. Koehler, J. of Low Temp. Phys. 2018.

Outline

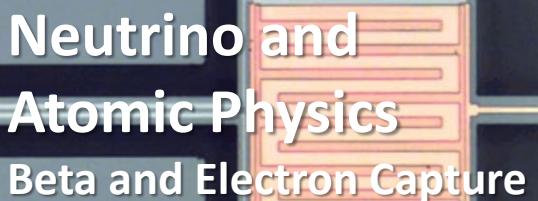
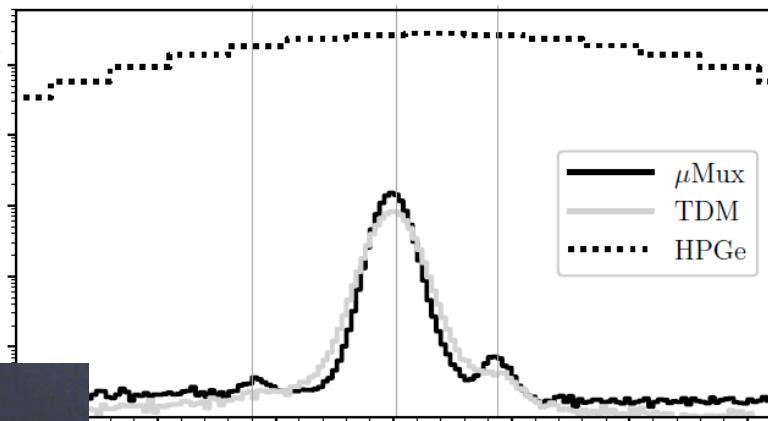
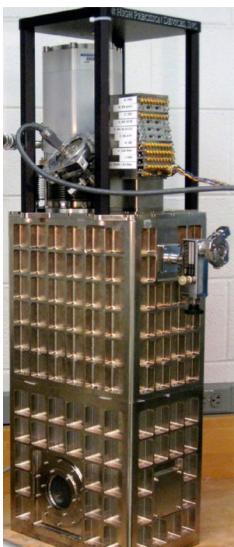
- What's a Microcalorimeter?
- Safeguards Applications
 - Gamma
 - X-ray
 - Alpha/Decay Energy Spectroscopy
- A Bright, Bold Future

A Bright, Bold Future

Nuclear Safeguards and Metrology

Nuclear forensics

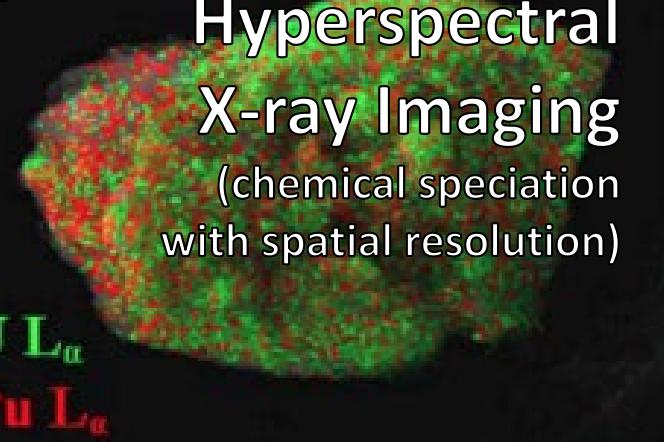
- Treaty verification
- Environmental monitoring



SEM+Microcalorimeter Array=

Hyperspectral X-ray Imaging

(chemical speciation
with spatial resolution)



3x
 $^{225}\text{Ac-PSMA}$

1x
 $^{225}\text{Ac-PSMA}$

Cancer Research (quantification of impurities)

Do you have a problem that could benefit from ultra high energy resolution?

